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16. ABSTRACT

A laboratory study is described in which model slabs and special loading equipment were installed specifically to study faulting of concrete pavements. The curling of slabs, pumping actions and development of faulting are discussed. Methods of preventing faulting are suggested.

It was found that some fines under faulted slabs can be ejected into the shoulder while pumping when slabs are curled. This ejected material could plug a drainage system or filter fabric. Methods of immobilizing these fines are needed.

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STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION
DIVISION OF CONSTRUCTION
OFFICE OF TRANSPORTATION LABORATORY

June 1980

FHWA No. F-7-33
TL No. 633170

MODEL SLAB FAULTING STUDY

Study Made by .... Soil Mechanics & Pavement Branch

Under the Supervision of .... R. A. Forsyth

Principal Investigator .... J. H. Woodstrom

Co-Investigator .... B. F. Neal

Report Prepared by .... B. F. Neal

APPROVED BY

NEAL ANDERSEN
Chief, Office of Transportation Laboratory

CONVERSION FACTORS

English to Metric System (SI) of Measurement

Quanity	English unit	Multiply by	To get metric equivalent
Length	inches (in)or(")	25.40	millimetres (mm)
		.02540	metres (m)
	feet (ft)or(')	.3048	metres (m)
	miles (mi)	1.609	kilometres (km)
Area	square inches (in^2)	6.432×10^{-4}	square metres (m^2)
	square feet (ft^2)	.09290	square metres (m^2)
	acres	.4047	hectares (ha)
Volume	gallons (gal)	3.785	litres (l)
	cubic feet (ft^3)	.02832	cubic metres (m^3)
	cubic yards (yd^3)	.7646	cubic metres (m^3)
Volume/Time (Flow)	cubic feet per second (ft^3/s)	28.317	litres per second (l/s)
	gallons per minute (gal/min)	.06309	litres per second (l/s)
Mass	pounds (lb)	.4536	kilograms (kg)
Velocity	miles per hour(mph)	.4470	metres per second (m/s)
	feet per second(fps)	.3048	metres per second (m/s)
Acceleration	feet per second squared (ft/s^2)	.3048	metres per second squared (m/s^2)
	acceleration due to force of gravity(G)	9.807	metres per second squared (m/s^2)
Weight Density	pounds per cubic (lb/ft^3)	16.02	kilograms per cubic metre (kg/m^2)
Force	pounds (lbs)	4.448	newtons(N)
	kips (1000 lbs)	4448	newtons (N)
Thermal Energy	British thermal unit (BTU)	1055	joules (J)
Mechanical Energy	foot-pounds(ft-lb)	1.356	joules (J)
	foot-kips (ft-k)	1356	joules (J)
Bending Moment or Torque	inch-pounds(ft-lbs)	.1130	newton-metres (Nm)
	foot-pounds(ft-lbs)	1.356	newton-metres (Nm)
Pressure	pounds per square inch (psi)	6895	pascals (Pa)
	pounds per square foot (psf)	47.88	pascals (Pa)
Stress Intensity	kips per square inch square root inch (ksi $\sqrt{in}$)	1.0988	mega pascals $\sqrt{metre}$ (MPa $\sqrt{m}$)
	pounds per square inch square root inch (psi $\sqrt{in}$)	1.0988	kilo pascals $\sqrt{metre}$ (KPa $\sqrt{m}$)
Plane Angle	degrees (°)	0.0175	radians (rad)
Temperature	degrees fahrenheit (F)	$\frac{tF - 32}{1.8} = tC$	degrees celsius (°C)

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In design, construction and installation of the equipment: Jim Cox of Cox and Sons. In design and construction of the testing bed and reaction frames: Richard Spring, Dale Peck, Paul Jonas, Steve Rutter, Leonard Nordmann, Ralph Fitzpatrick, Lee Wilson, and Dave Wong.

In instrumentation design and construction and miscellaneous shop work: Joe Wilson and George Oki. In special plumbing and electrical work: Joe Langston, John Battanany, Coy Womack and Sam Heredia.

Special thanks to Leo Ferroni who was chief operator, caretaker, and trouble-shooter throughout the study, with help from Ed Budney and Jan Shetler.

The work of the drafting and typing personnel is also greatly appreciated.

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INTRODUCTION

Pavement faulting* continues to be the most serious problem affecting the performance of plain jointed portland cement concrete pavements. The problem has been extensively studied and the factors involved have been identified (References 1,2,3,4). They are: (1) free water under the slabs, (2) deflection of slabs under heavy moving wheel loads, and (3) unstabilized or erodible material under or adjacent to the slabs. These factors combine to produce a pumping action, resulting in an accumulation or buildup of material near the joint, with the greater amount being under the approach side of the joint. This buildup creates the condition known as faulting.

To eliminate faulting, the combination of contributing factors must be eliminated. Preventing the entry of all water through joints and cracks is not considered feasible. A joint sealant system to provide watertight seals year round and over a period of years has not been developed. The sealants do prevent the entry of detrimental fine materials. To eliminate the free water factor, however, drainage must be provided.

The problem of slab deflections at joints due to heavy wheel loads over curled slabs is more difficult to solve. While dowels across joints would be expected to improve load transfer, the high cost of installation and unsatisfactory performance in California (as well as some other states) has all but eliminated them from consideration.

*The term "faulting", as used in this report, refers to the vertical displacement of concrete pavement slabs at joints.

The use of cement treated base to provide nonerodible support for the pavement slabs has been used in California for more than 30 years. While the quality has been upgraded periodically, the surface is still erodible to some degree. Under typical base construction practice, excess material is placed, compacted, trimmed to grade, then recompacted. The material loosened by trimming is often not properly recompacted due to partial hydration of the cement or other reasons. Also, the asphalt curing membrane usually penetrates the base to some extent, adhering to the pavement slabs when placed. As the slabs curl upward, the membrane often pulls loose from the base, bringing some particles upward with it, and leaving other loose particles exposed to the pumping action. Bases constructed with lean concrete (5) or asphalt concrete (6) have been found to be satisfactory and much more abrasion resistant.

Untreated base material typically used in shoulder construction has been found to be a major source of the fines found under faulted joints (1). To prevent faulting, this source must be eliminated. Suggested methods include stabilizing the portion of the outer shoulder adjacent to the slab with asphalt or cement, or isolating the material from the slab by use of a filter fabric.

While a number of experimental features which may be effective in reducing faulting have been constructed, it could require several years of field trial before performance comparisons with routine procedures can be made. For this reason, an accelerated method of determining performance was considered desirable.

The Portland Cement Association has used model slab techniques for such things as determining load transfer across joints (7). By using electrically controlled air-hydraulic loading methods, they were able to simulate millions of wheel loads in a relatively short time. It appeared logical that a similar system could be used to develop faulting under laboratory conditions and in finding procedures for preventing faulting.

A further incentive for accelerated testing is the rehabilitation needed for a large number of our existing concrete pavements. Structurally sound pavements can be ground to restore riding quality at reasonable cost. However, mitigation is needed to prevent the recurrence of faulting since faulting can and does develop again in relatively short period of time on ground pavement projects.

Following discussions with engineers in Design, Construction, and Maintenance, it was decided to initiate research to conduct an accelerated testing program. The proposed objective was the evaluation of new methods to minimize the occurrence of faulting.

The project included construction of a model structural section in the Laboratory complete with two concrete pavement slabs. Equipment was to be installed to provide timed cyclic loading on each side of a joint to simulate moving wheel loads. Heat was to be provided under the slabs to help induce curl, and water made available to provide a medium for transporting loose material.

CONCLUSIONS

From the findings of this and other studies, the following conclusions are considered warranted.

1. Considerable upward curl of concrete slabs results from drying shrinkage alone. Additional curl can be induced by cooling the top of slabs, creating a thermal gradient between top and bottom. Under field conditions, this gradient occurs daily during the early morning hours.

2. Faulting can be made to occur on model slabs under laboratory controlled conditions with free water, available fines, and loads applied to slabs which are curled upward.

3. If fine materials can be prevented from getting under the slabs, or being removed from the base, faulting will not occur even with the other contributing factors present.

4. Some of the fines under faulted slabs can be ejected into the shoulder during pumping when slabs are curled. This may plug a drainage system or filter fabric. A means of immobilizing those fines is needed.

5. Faulting increases at slower rates in semi-arid regions of the state than in the mountain and coastal regions where more rainfall, or equivalent moisture in the form of snow, occurs.

IMPLEMENTATION

Most of the recommendations in this report have already been implemented. New standard plans have been issued for drainage installations with slotted pipe, either cement or asphalt treated permeable material, and filter fabric. In almost all areas of the state, lean concrete base is specified under PCC pavements. Drainage is also being installed on numerous older pavements.

EQUIPMENT, TEST BED AND INSTRUMENTATION

Following discussions with manufacturer's representatives and our own mechanical and electronic engineers, specifications were developed for electronically controlled hydraulic cyclic-loading equipment for simulating moving wheel loads. Bids for the equipment were requested in January, 1977. While three companies responded, each proposed at least one exception to the specifications. Consequently all proposals were rejected. After some revisions in the requirements, the project was readvertised in April, 1977. Four companies submitted bids. James Cox and Sons of Colfax, California was awarded the contract. The equipment specifications are included in the appendix.

While the equipment purchasing and construction process was going on, work proceeded on the construction of the testing bed and reaction frames. A metal frame building with suitable access and the necessary utilities was made available for the project. The walls of the test bed consist of reinforced concrete for the reaction frame base, and concrete blocks largely enclosing an area 11 feet x 28 feet approximately 32 inches in height (see Figure 1). One end was left open for equipment and material access. Approximately 17 inches of subbase material was placed and compacted in 3 separate layers (see Figures 2 and 3). Pipes for hot water to heat the bottom of the slab were then installed (see Figure 4). Because of the extreme length of pipe (over 200 ft), two separate circulation systems were used to speed the heating process. Cement treated base (CTB) was then placed and compacted to a depth of 5 inches (see Figures 5 and 6). Liquid asphalt was used as a curing membrane. Two 8 ft x

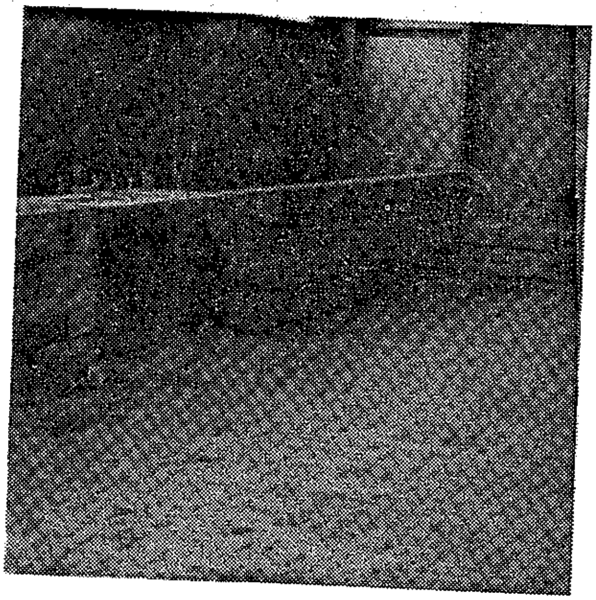


Fig. 1
Walls and floor of test bed.

Fig. 2
Compacting subbase.

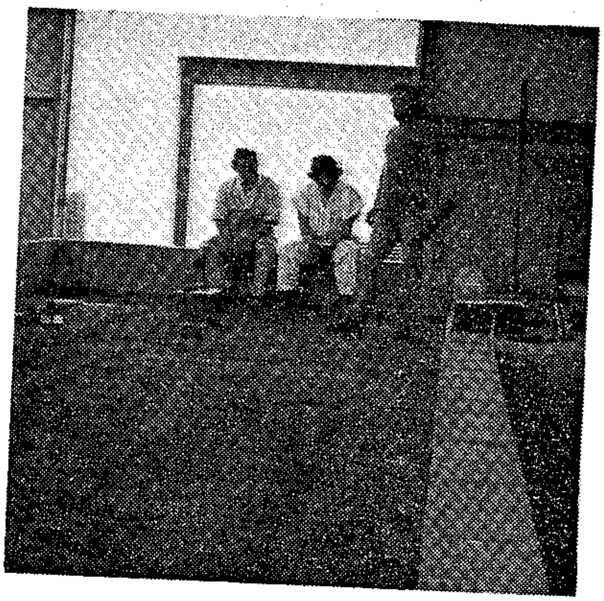


Fig. 3
Compaction test on subbase.

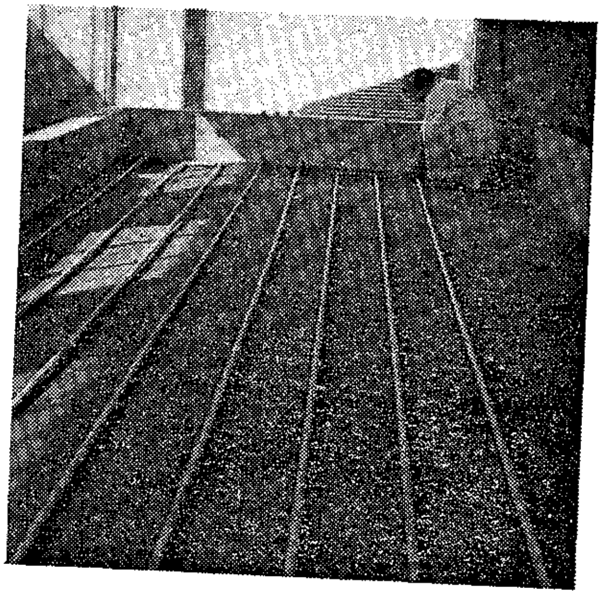


Fig. 4
Installation of hot water pipes for heating slabs.

Fig. 5
Compaction of cement-treated base.

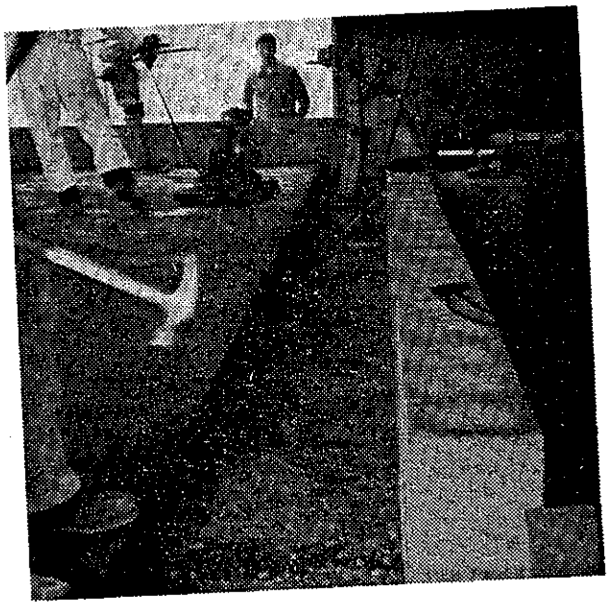
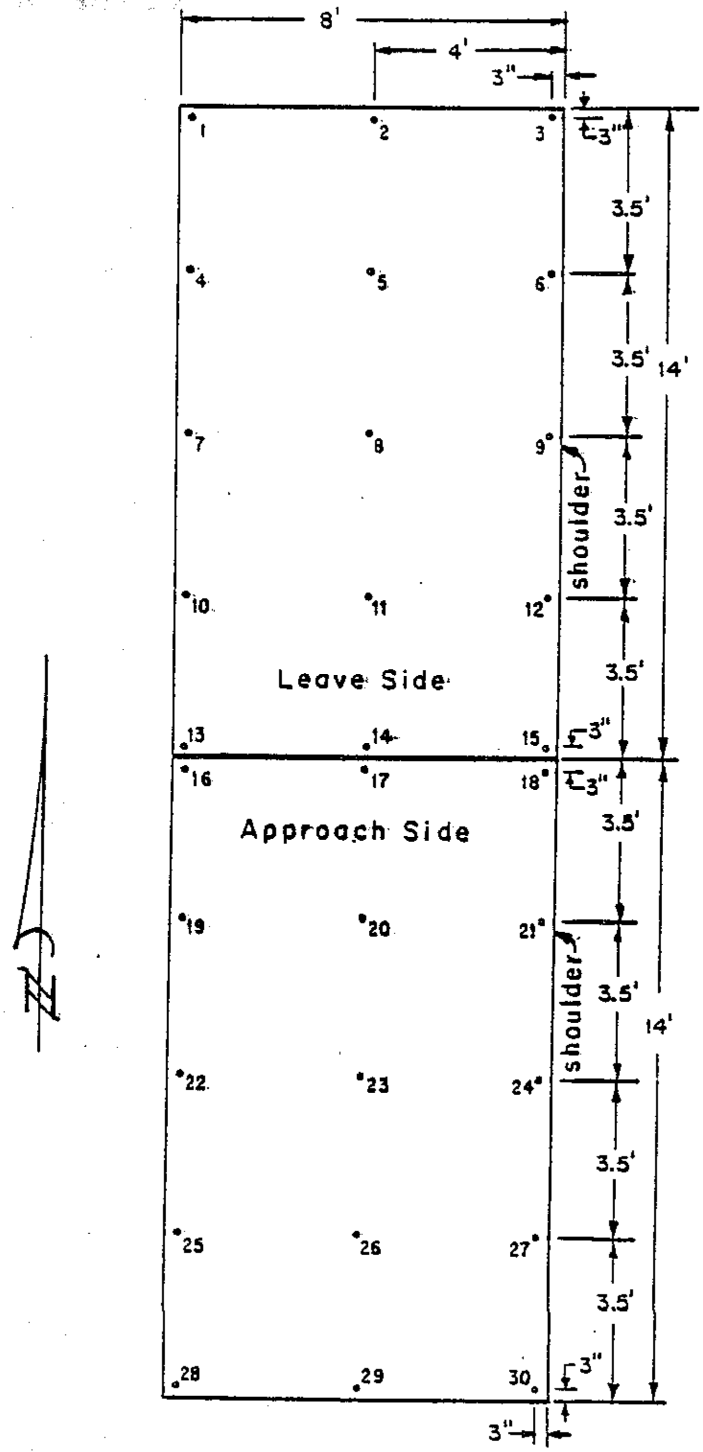


Fig. 6
Cement treated base
construction completed.

14 ft x 9 in. deep concrete slabs were then constructed. Since the loading equipment was not available to assure cracking through a weakened plane, a full depth insert was used to form the joint. An aggregate base shoulder completed the testing bed. The structural section was built with a 1% cross slope and a 1% grade to provide drainage.

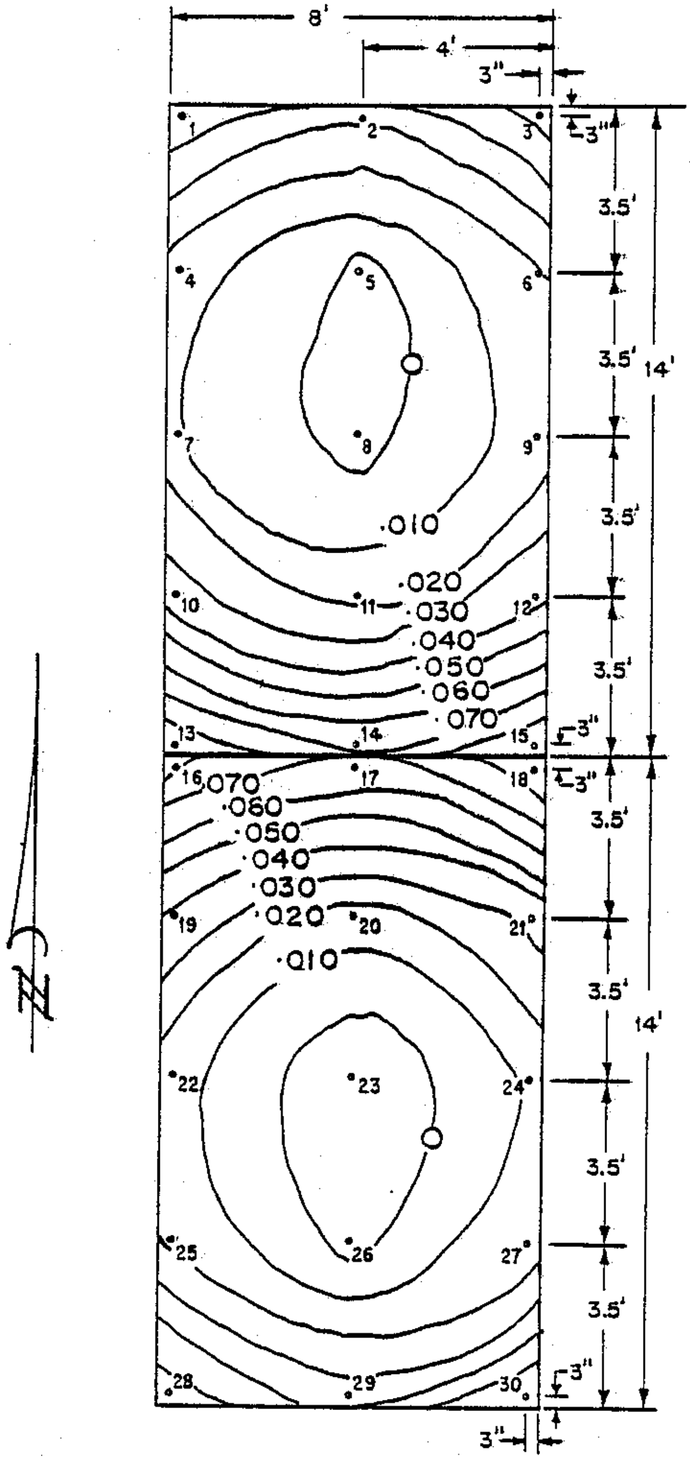
A set of 4 thermocouples was installed in and under each slab to monitor temperature. One of each set was placed (1) under the CTB, (2) on top of the CTB, (3) at the midpoint of the concrete slab, and (4) 1 inch under the concrete surface. Gage points were epoxied to the slab surface to measure curl, deflection, or other vertical slab movements as shown by Figure 7.

During the approximately 7 month period between completion of the test slab and equipment installation, temperature and curl gages were monitored periodically. The circulating hot water effectively raised the temperature at the bottom of the slab. However, due to the high thermal conductivity of concrete, it also raised the temperature throughout the slab. This reduced the thermal gradient and the amount of induced curl. During the monitoring period, the water temperature was held to about 110°F and slab temperature was not raised above about 90°F. When the water was not circulating, temperatures throughout the structural section were uniform and approximately the same as ambient. As the concrete dried, upward curl increased daily, with a maximum of 0.03 inch after 7 days, 0.05 inch after 14 days, and a peak of about 0.10 inch in 3 months, although total curl varied with changes in temperature. An isogram of the curl after 6 months with uniform temperature of 56°F is shown in Figure 8, at which time maximum curl was about 0.085 inch.



LAYOUT OF POINTS FOR CURL MEASUREMENT OF SLABS

Figure 7



ISOGRAM OF CURL

SIX MONTHS DRYING–NO LOADING

Figure 8

Testing equipment was delivered and installed in late January, 1978. Overall views of the layout and close-ups of significant components are shown in Figures 9 through 12. Actuators were installed about 30 inches from the shoulder to represent wheel track loading. Steel 8 in. x 10 in. blocks with thin neoprene bearing pads approximating the tire print of a single truck wheel were used to distribute loads. The reaction frames were designed to deflect less than 0.005 inch when a 10,000 lb load was applied. In Figure 11, the near actuator applies the first load on what will be referred to as the "approach" side of the joint. The second actuator applies a load to the "leave" side of the joint.

The equipment was tested for a period of about 6 weeks and, after minor adjustments, was found to meet the specifications. Loads can be programmed from 0-12,000 lb on each actuator. The machine automatically shuts down if loading exceeds 12,500 lb. Times of achieving the programmed loads, unloading, or delay periods can be adjusted from milliseconds to 1 x 10^8 seconds. The limiting factor proved to be the unloading rate since it requires about 10 milliseconds for a 10,000 lb load to be completely removed by the hydraulic system. This was satisfactory since that was the calculated time for a moving load at 50 mph to travel 9 inches, and had aready been selected as the programmed time.

These features provided considerable flexibility in programming the loading and unloading of the actuators. Safety features provided for automatic shutdown if a malfunction occurred or electrical power supply was disrupted. In case of shutdowns, a manual restart was required so that

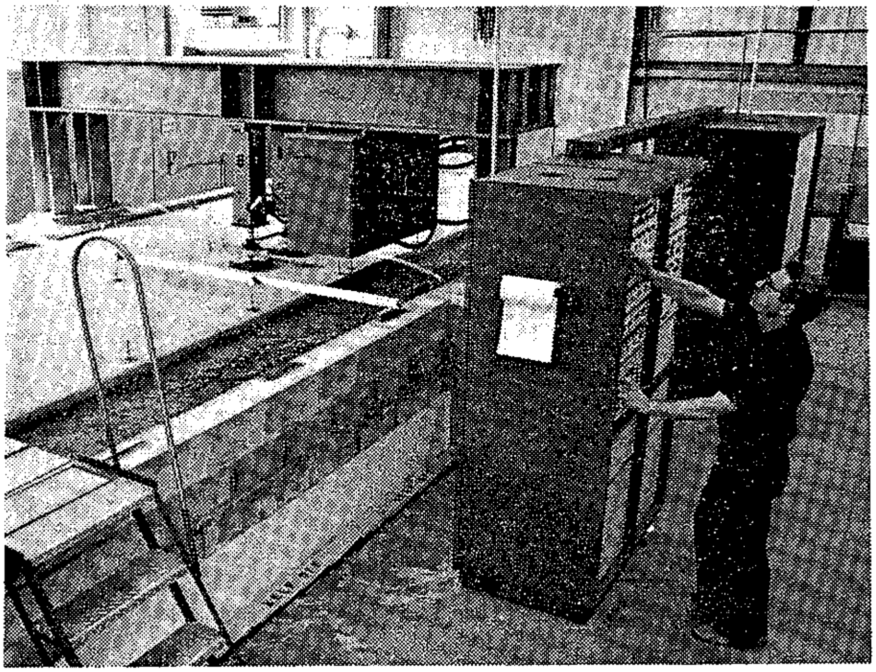


Fig. 9
Overall view of equipment and test bed.

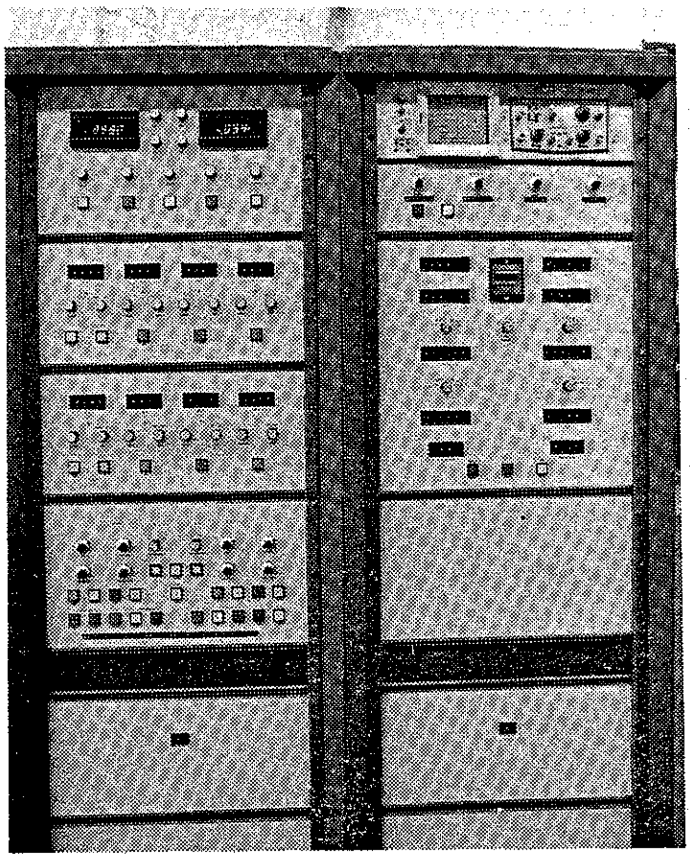


Fig. 10
Control Console

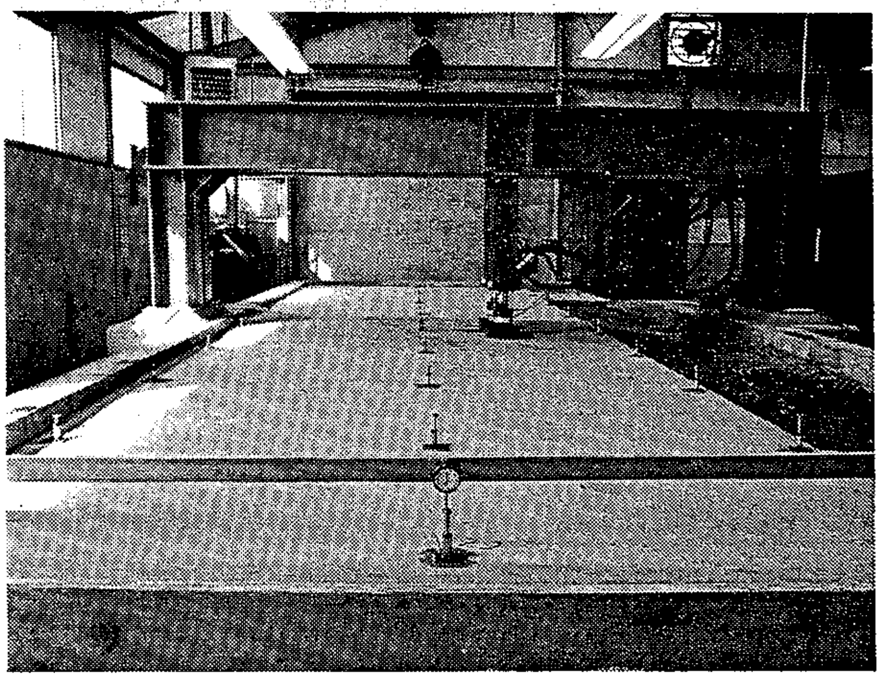


Fig. 11
Gage plugs, gage and actuators.

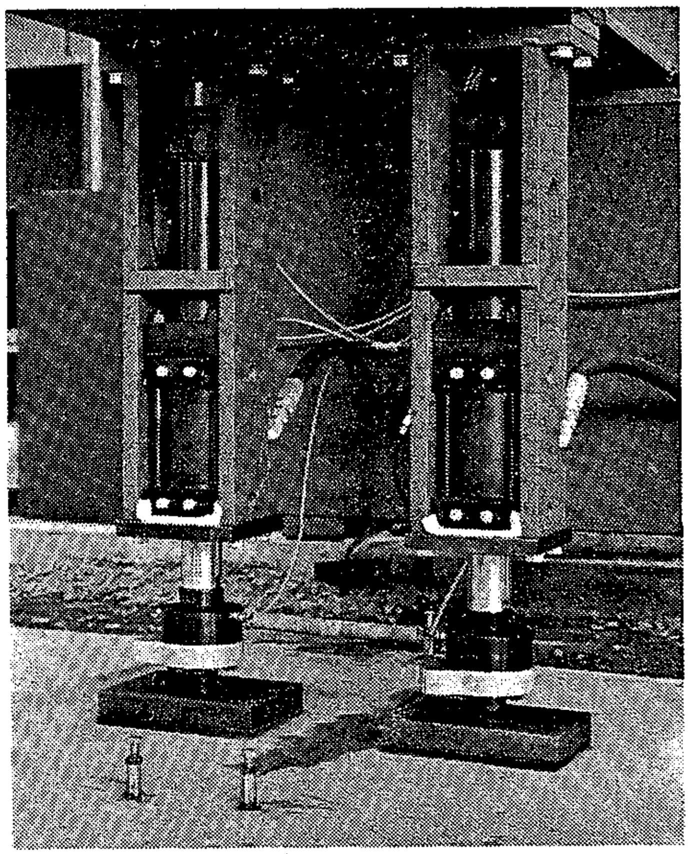


Fig. 12
Closeup of actuators.

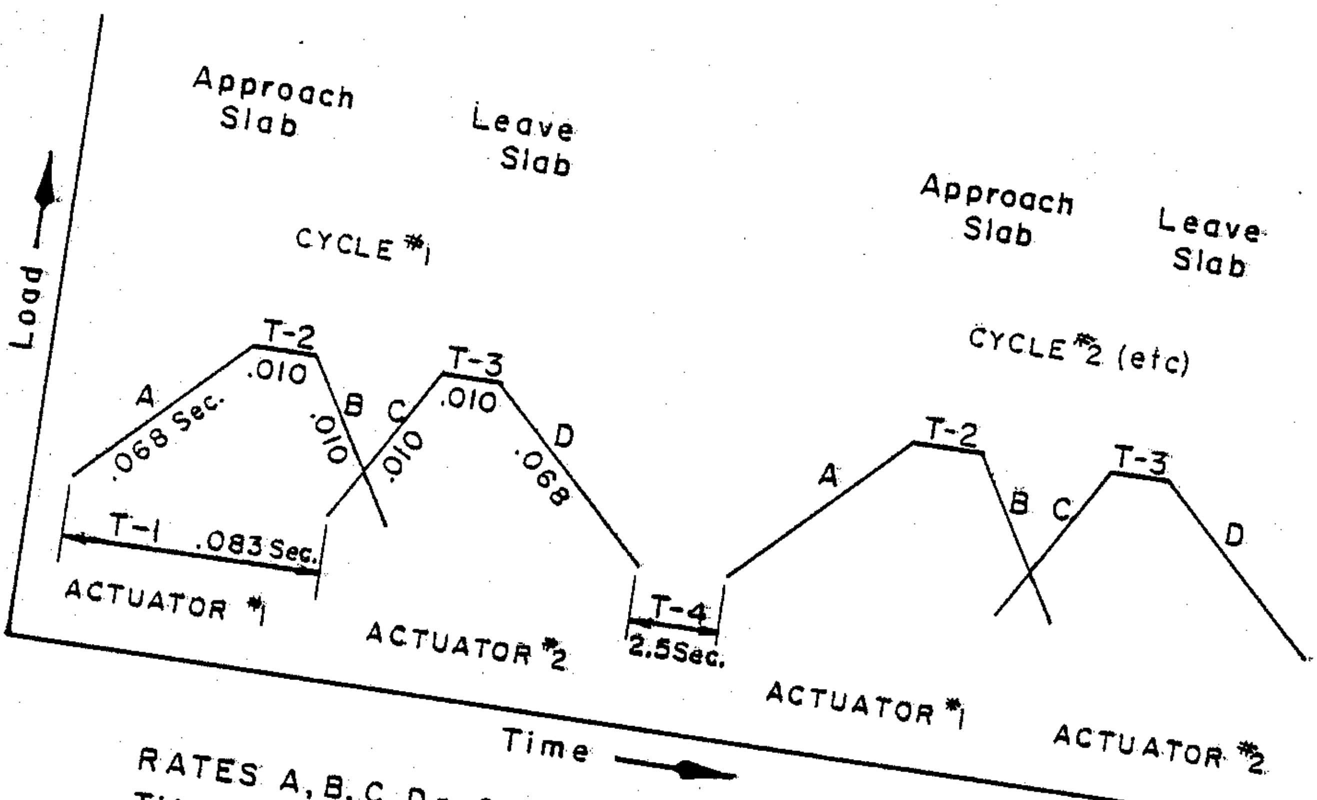
a check would be made to determine the cause of the malfunction. The equipment normally operated continuously, with only periodic checks necessary.

TESTING

Considerable experimentation was required to establish the desired loading rates and time sequences. All functions were programmed through a dual digital ramp generator with adjustment based on load cell feed-back information shown digitally and on an oscilloscope. The programmed information was as shown in Figure 13. The times T2 and T3 were entered to prevent overshoot of the planned loading rate, and proved to be quite satisfactory as observed on the oscilloscope. Initially, loading was applied at 9,000 lbs on each actuator. A preload of 100 to 300 lbs was kept on the actuators to prevent loss of contact with the base plate.

Dynamic and static deflection measurements were made with a 9,000 lb loading with the application of heat under the slab to maximize the curl. The results are shown in Table 1. Only the gage points near the joint (13 through 18) were read for static loading. Gage points 1-6 and 25-30 (see Figure 7) indicated no movement under dynamic loading. When the area under the slabs was flooded with water, a definite cushioning effect was noted with dynamic deflections reduced to about half the original values.

By mid-February, 1978, attempts to create a faulted condition were begun. Loading rates were set to simulate a vehicle moving at 50 mph, water was added through the joint periodically, and the bottom of the slab heated at times to induce more curl. In March, no faulting had occurred although water was noted ejecting from the joint occasionally, and mud spots were found on the reaction frame some 4 ft above the slab. By opening the leave shoulder, it was observed that fines were missing from the graded shoulder aggregate, and migration of fines under the slab could be detected.



RATES A, B, C, D = .001 SEC. TO 100K SEC.
TIME 1,2,3,4 = .001 SEC. TO 1000 SEC.
AMPLITUDE = 0v TO 10v RESOLUTION IN .001 VOLT STEPS

LOADING AND TIMING RATES

Figure 13

TABLE 1

DEflection Measurements, 9,000 lb. Load (Inches)

	Leave Side					
	Dynamic			Static		
Gage Points (See Fig. 7)	7 .000	8 .001	9 .002			
" "	10 .001	11 .007	12 .011			
" "	13 .008	14 .020	15 .025	13 .012	14 .025	15 .032
	Approach Side					
" "	16 .004	17 .019	18 .021	16 .006	17 .018	18 .021
" "	19 .001	20 .008	21 .008			
" "	22 .000	23 .002	24 .002			

A calibrated gate valve used to meter a small amount of water through a hose into the joint would occasionally shut off due to the accumulation of grit in the small gate opening. To correct this problem, a reservoir made from a concrete block and controlled with a float valve was installed in the shoulder. After several trials, it was finally located in the shoulder at the mid-point of the leave slab and allowed to spill on top of the shoulder material.

As of April, 1978 no significant faulting had occurred. A 4 inch hole was opened in the approach slab near the joint to observe action below the slab. Water and fine material under considerable force could be felt at the base surface during the pumping action. In spite of the changes in timing and loading, it was difficult to detect any significant difference in pressure or material movement. With the core hole left open, fines would build up, indicating the action needed for faulting was taking place. A plastic cover was installed in the core hole at the bottom of the slab so that material movements could be monitored.

Cores were then drilled at the joint near the inside slab edge. Here, again, the movement of fines were readily apparent. Migration of material was observed at least 7 feet from the shoulder. If left open, the holes would occasionally become completely filled with fines.

In May, some faulting occurred, reaching a maximum of 0.025 in. in 4,700,000 cycles (4.7 MC). A portion of the shoulder on the leave side of the joint was removed so that the pumping action could be observed at that location. It was found that considerable force was exerted on the water during loading, the effect of which was observed for 5 feet along the slab edge. When graded concrete sand was used to rebuild the shoulder, it was found to quickly become classified, with fine material removed from the bottom portion, leaving undisturbed graded sand at the top. Visual examination of a cross section of the shoulder material clearly revealed the zone where fine material had been removed. The line started at the slab edge about 2 inches above the bottom and extended to about 6 inches high at a point some 8 inches into the shoulder.

In June, some 6,000-8,000 lbs. of steel was placed on the free end of the approach slab to provide restraint to the loading at the opposite end. Faulting remained about the same until July when it reached 0.050 in. (7.0 MC). This amount was considered inadequate in terms of creating a faulted pavement condition.

By August, it was obvious that additional measures were necessary to create pavement curl. A review of old profiles taken with the California Profilograph indicated that in the early morning hours, pavements could be curled upward as much as 0.100 in. compared to afternoon measurements. Since curl on the test slabs was only a fraction of that amount (other than initial curl due to drying), ice was placed on the approach slab to create a greater temperature differential between top and bottom. This induced an additional 0.060 in. of curl. This effect was only temporary, however, since the water from the melting ice entering beneath the slab, quickly reduced the thermal gradient and slab curl. Still, faulting was increased in one day from 0.050 in. to 0.070 in. (8.8 MC), which was most encouraging.

After a few days, ice was added again with provisions to prevent the ice water from getting under the slab. Faulting increased to 0.100 in. When ice was used 2 days later, only 0.010 in. of curl developed. Later, it became obvious that after increasing the faulting, approximately a week was needed between icings to allow stress relaxation before significant curling could again be forced. With a few more icing treatments, faulting reached 0.200 in. by late September, and was considered to be at a stage where testing could be suspended and an evaluation made of fine material movement under the slab.

Slab Removal and Replacement

In field studies of faulted slabs, portions of slabs adjacent to the joint were removed. For this study, the ends of the slabs were lifted to minimize disruption to the underlying materials. This was accomplished by use of 50 ton hydraulic jacks and steel jacking frames bolted to the slabs. One end of each slab was raised about 18 inches. Wooden blocks were then placed under the slabs for support since neither the jacks nor the bolts would sustain the loading for the period of time needed to examine the below-slab surfaces.

Figures 14-17 show the base surfaces. Some of the coarser aggregate particles (3/8-1/2 in.) shown in Figure 15, probably came from either the bottom of the slab or the top of the CTB, as well as from the shoulder. Since all aggregates used, including the shoulder, were supplied by the same company, the source of coarser particles could not be identified. The small mound seen in the right center of Figure 15 is a buildup under the plug in the core hole. This was a result of failure to screw the plug

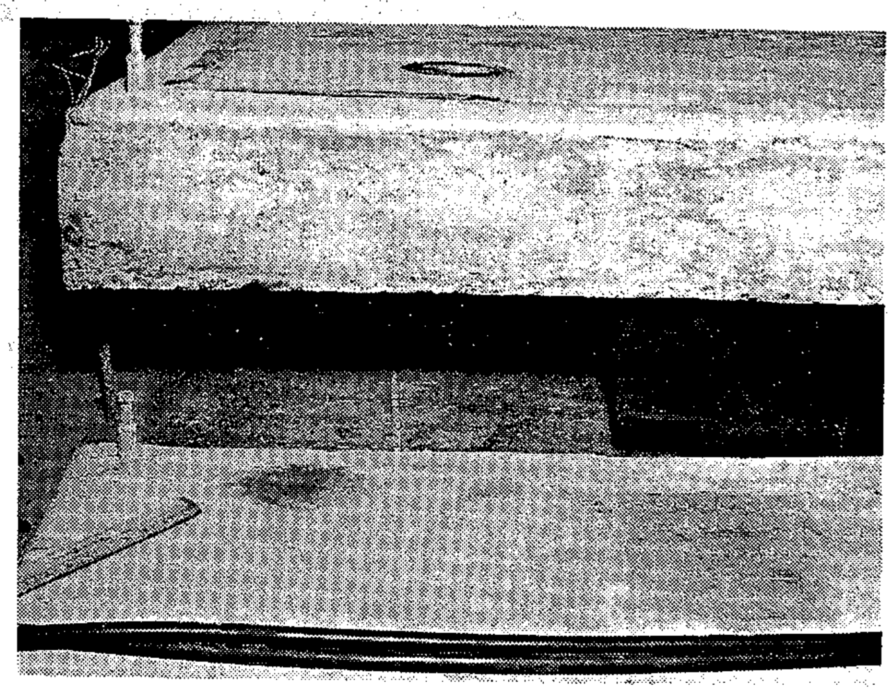


Fig. 14

Deposit of aggregate particles beneath raised approach slab.

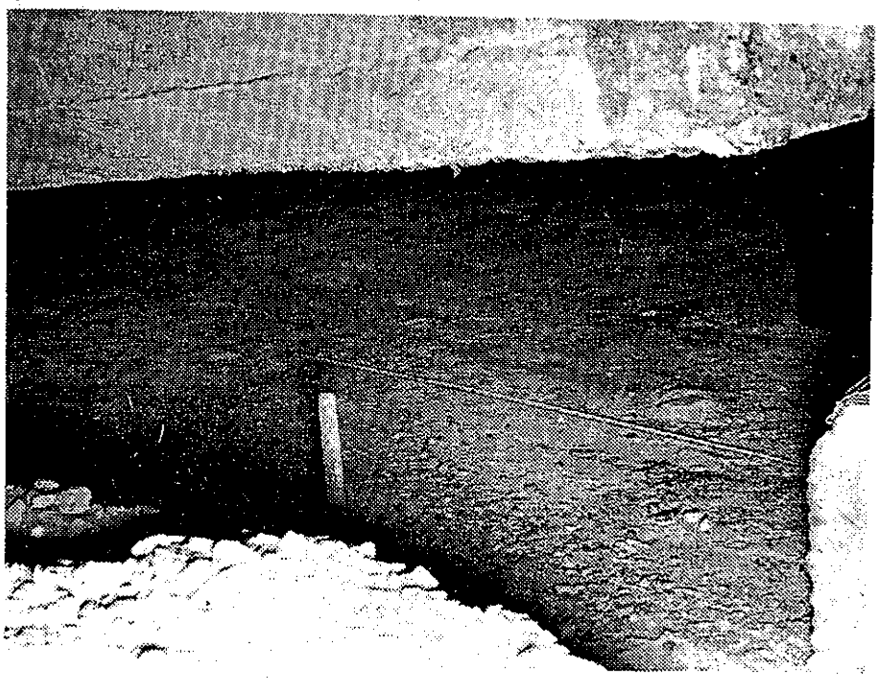


Fig. 15

Looking under approach slab from "shoulder" area. Showing close-up of migrated material.

down sufficiently the last time it was removed for observations. Figure 16 shows the buildup under the approach slab on the inner side. The fines extend about 4 ft from the joint at this point and about 5 ft from the outer shoulder. Figure 17 shows the surface near the joint with both slabs raised. Abrasion of the edge of the leave slab (right side) due to pumping of aggregate particles can also be seen.

On completion of the above observations, the migrated materials were removed by water and squeegee. The base under the leave slab, for about 16 sq ft near the joint and shoulder, was found to be badly scoured. As much as a half inch of base was removed in numerous spots. This condition was not found under the approach slab. The bottoms of both slabs indicated considerable abrasion, however.

Since the destruction, removal and reconstruction of the base and slabs would have been highly labor intensive, it was decided to attempt replacing the slabs for reuse in further studies. Placing the slabs back into position where all gage points fit properly and read approximately what they had originally proved to be difficult, but was eventually accomplished.

Fault Prevention

To demonstrate that faulting could be prevented by isolating shoulder material, a strip of non-woven filter fabric was placed on the slab edge and extended out on to the CTB under the shoulder. A slotted drain pipe was installed adjacent to the edge of the approach slab and the shoulder

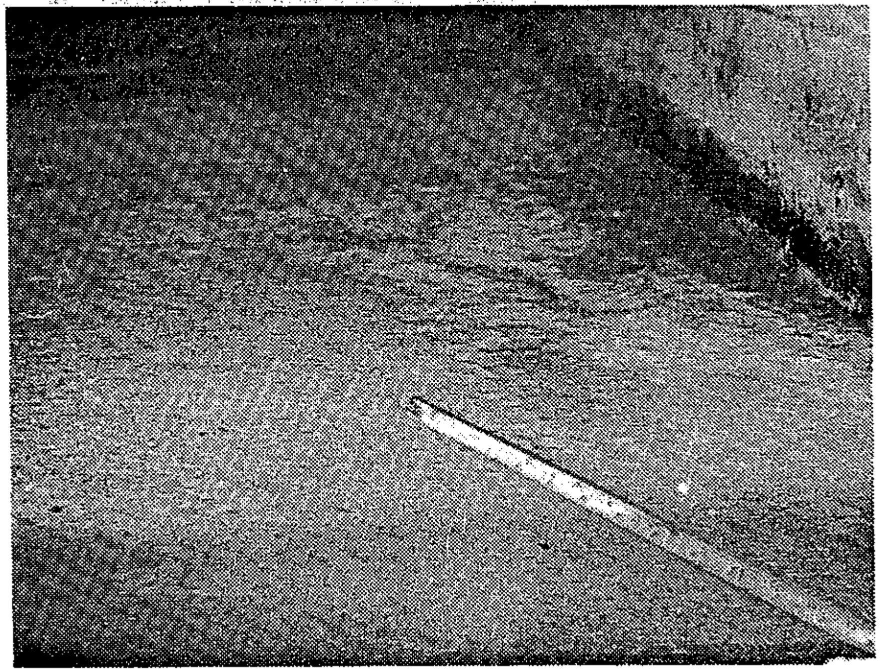


Fig. 16

Deposit of material along inside wall of test bed.

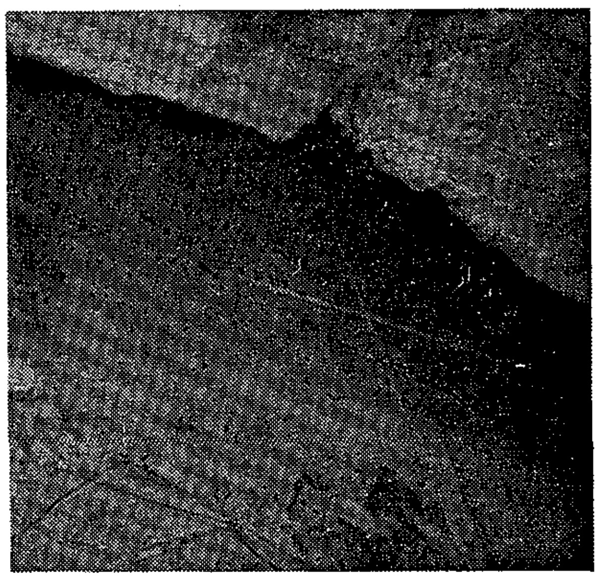


Fig. 17

View under leave slab with both slabs raised.

was built with aggregate base. Water could enter under the leave slab and be pumped to the approach side until picked up by the drain. However, fine material could not penetrate the fabric.

After about a month of loading under dry conditions to assure proper seating of the slabs, water was added as before. For over a month, this pumping was allowed to continue. Two times during that period, ice was added to induce curl. Through the core holes, water could be observed under the pumping action, but remained perfectly clear. The drain worked satisfactorily, continuously removing water. It also remained clear with no indication of fine particle movement. Since further testing under these conditions was considered nonproductive, the filter fabric was removed so the shoulder material was again available to induce faulting.

Repeat of Faulting Tests

Pumping was again started. After 2 icings, faulting of 0.060 in. developed after which testing was temporarily suspended. Upon resumption of testing, ice was used 6 times in a 30 day period resulting in a 0.255 in. fault. These results clearly indicated that faulting could develop in a fairly short period by creating the necessary conditions, i.e., curled slab, water, available fines, and heavy wheel loads.

During the latter testing period, the loads used were in the range of 6500 to 7500 lbs. This indicates that while heavier loads may supply greater energy to water movements, total load need not be large to cause faulting.

Unfaulting Attempts

Following another period of inactivity, an attempt was made to unfault the slab. Early in the testing it was noted that occasionally fines would be forced up through the shoulder adjacent to the edge of the approach slab. If an opening were made in the shoulder, it would fill up with fines pumped out from under the slab. To further observe this phenomena, the approach shoulder was removed for a length of about 7 ft from the joint. The leave shoulder was also removed for about the same length so that additional material could not get under the slab. It was theorized that, if sufficient fines could be removed, the faulted condition would be reduced. With water being added continually, fines were ejected readily, though not along the entire edge at the same time. The material would accumulate at 2 or 3 points after which the accumulations would develop at other points. When the buildup on the shoulder reached 3 or 4 in. in depth, ejection slowed considerably and usually stopped. By removing the material, the action could be reinitiated.

Although more than 5 gallons of material were removed from under the slab, there was no significant decrease in faulting. Apparently, the pumping which is along separate channels leaves adequate support for the slab. Since this method of unfaulting was not successful, it was abandoned.

Before going to the next step in testing, the shoulders were replaced, and curling was once more induced. This resulted in more material being pumped in to fill any voids created by the unfaulting attempt. The resultant fault was 0.304 in.

Porous Concrete Shoulder

The next step was the installation of a porous concrete shoulder for about 7 ft on the approach side with slotted pipe at the bottom of the last few feet. The concrete was made with 1 in. x No 4 concrete aggregate, 10% cement by weight, and a water-cement ratio of 0.40. This was not a test for determining the adequacy of the material to remove water, but rather to determine if drains installed on faulted pavements might become plugged from ejection of fines. For about a month, water drained quite readily. However, after icing the slab and pumping, the flow of water stopped completely. An examination of the porous concrete after removal revealed that the voids throughout the entire length and cross-section were completely plugged (see Figures 18-21). These results indicate that drainage installed during rehabilitation of faulted pavements may not function as intended for any appreciable length of time unless (1) measures are taken to prevent ejection of the fines already under the slabs, and/or (2) provision is made in edge drain design to allow periodic flushing.

Fines Stabilization

Attempts to find materials and means of stabilizing the fines are now being made. A chemical grout, Cyanaloc 6, made by American Cyanimide, is being investigated as one possibility. The material can be formulated to be very fast-setting, and returns to its original height after compression. The effect of aging on this quality is unknown at this time. The chemical grout was recently injected under the model slabs, using a shop made pressure

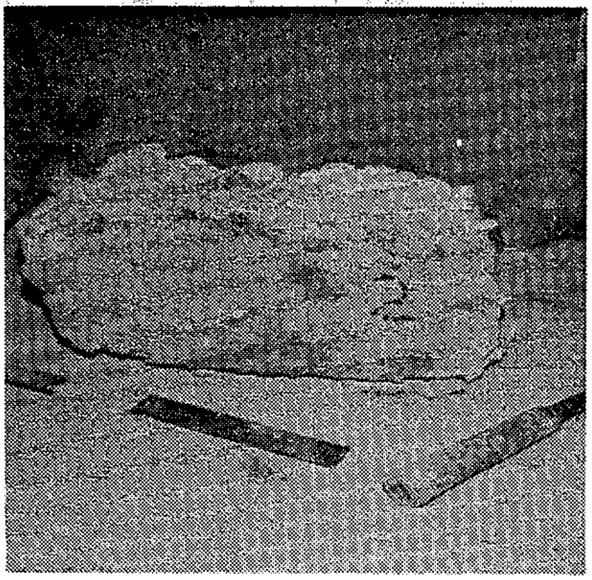


Fig. 18

Porous concrete plugged - edge adjacent to slab.

Fig. 19

Porous concrete - edge away from slab.

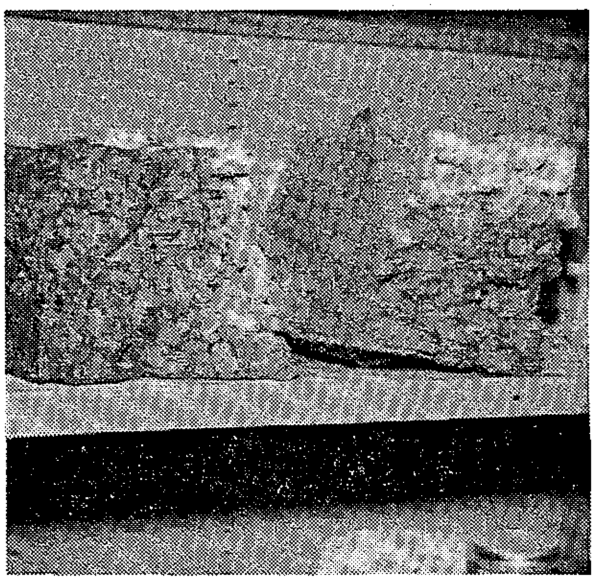


Fig. 20

Broken section of porous concrete - all voids filled.

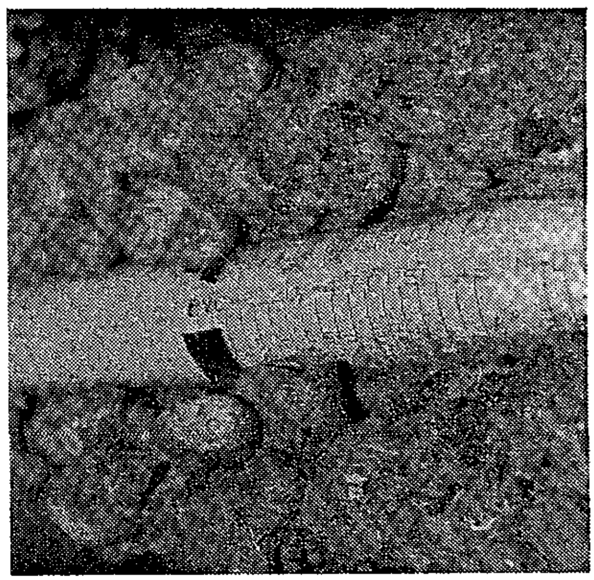


Fig. 21

Slotted pipe in porous concrete.

tank. A pressure of approximately 20 psi was used. Initial tests indicated significant reductions in deflection. On the approach side, deflections decreased from 0.028 in. to 0.018 in., and on the leave side, from 0.012 in. to 0.008 in., all under a 9,000 lb load. However, pumping with water present removed some of the grout and fines from under the approach side and allowed deflections to increase greatly, from 0.018 in. to about 0.060 in., (after approximately 1.0 MC) indicating the creation of a large void. Deflections on the leave side have remained unchanged, which indicates some measure of success.

Obviously, much more work is needed in this area. Other materials are now being studied, and likely candidates will be tested. One unknown factor which is considered highly significant, is the moisture content of the fines under the slab. It may be that the failure of the grouting effort for the project was due to dilution of the chemical by the moisture already present. Future efforts on this stabilization study will be covered in a report planned for 1981 on another project, "New Materials and Techniques for the Rehabilitation of Concrete Pavements".

DISCUSSION

The testing reported here demonstrated that the faulting phenomenon can be reproduced under laboratory conditions on an accelerated basis. Although actual field conditions were not duplicated, the mechanisms associated with faulting were duplicated. The conditions necessary for faulting to occur will be subsequently discussed individually.

Slab Curl

Since the model slabs were in place about 7 months before the loading equipment was installed, it was possible to study the slab movements quite thoroughly. As the concrete became dry, shrinkage caused an upward curl, finally attaining about 0.100 inch. By applying heat with infra-red lamps to the surface and cold water below the slab, curl could be reduced. When temperatures at the top and bottom of the slab were equalized, curl returned to its peak. This indicates that what might be considered permanent curl may be induced at an early age. It is not the temperature that causes curl (disregarding the shrinkage curl) but rather the differential temperature between the top and bottom of slabs. When ice was placed on the model slab and ice water penetrated to beneath the slab, the curl which had been forced by the original temperature differential was quickly reduced.

Another factor affecting curl is moisture differential between top and bottom of slabs. During slab removal operations, it was noted that the bottom of slabs are almost invariably damp. This difference in moisture can also accentuate the upward curling tendencies.

One additional factor affecting curl is the type of aggregates used in the concrete. Some aggregates cause considerably more shrinkage than others. The source used in the model slab concrete is about average in shrinkage characteristics of those used in California.

It was found that when curl was induced by adding ice, it took about 45 minutes for the maximum to be reached with the peak being maintained for only about 15 minutes. A slow but steady reduction in curl then took place over the next period of approximately 2 hours.

The work of New York State on pavement curl (8) shows that under field conditions, a 30-40°F temperature differential between top and bottom of slabs occurs twice each day, with as much as 0.0028 in. of curl induced for each degree of gradient. This indicates that an upward curl of slabs at the joints may often reach 0.100 in. The short period of peak gradient (maximum curl) is also confirmed by their findings. They also found that the length of slabs, and the presence (or absence) of reinforcement or dowels had no effect on curl.

The amount of upward curl most conducive to faulting is probably only present for about 6 hours each day in the field. In laboratory tests using ice, the time period was approximately 2 hours. If this latter indication is true, only about 2500 or 3000 loading cycles during each icing period were effectively causing faulting.

Temperature gradients can also tend to force slabs to curl downward at joints. While this action was not investigated since it would not be a condition conducive to faulting, it is a possible factor affecting pavement performance.

Loading and Deflections

An almost limitless number of combinations of rate and amount of loading were available with the equipment installed for this project. While it would have been desirable to have tested various combinations, this was not possible due to time constraints. For most of the testing, a simulated vehicle speed of 50 mph was used, along with nominal loadings of 7000 or 9000 lbs.

As seen in Table 1, the maximum dynamic deflections when loading was initiated were 0.021 in. on the approach side and 0.025 in. on the leave side. Static deflections were 0.021 in. and 0.032 in. respectively, for the same load. Recent measurements taken after faulting had been induced, indicated significant changes. Maximum dynamic deflection on the approach side was 0.028 in., and only 0.012 in. on the leave side. Maximum static deflections were 0.022 in. and 0.010 in. respectively. This change is likely due to shifting of underslab support. The fact that both slabs have undergone some 20,000,000 loading cycles, and the approach slab has been stressed by several ice applications, may also be a factor.

The deflection of the leave slab provides the force for the pumping action. With upward curl, more deflection is possible. However, it was not found necessary during this study to induce additional curl on the leave slab in order to cause material movement and faulting.

Pumping

When the material under the slabs was dry, it was observed through the core holes that fine material was being shifted to some extent. However, under field conditions, it is unknown whether material is ever sufficiently dry to be blown by air in sufficient amounts to cause faulting. With water present, these fines can be moved in large quantities. By removing most of the leave shoulder, fine material could be observed moving from the shoulder area to beneath the slab.

The precise location of the maximum pumping force appears to change frequently. At times, water and fines were temporarily ejected from the joint. Similar short periods of pumping action were noted at the core holes. This selectivity is probably the result of resistance caused by a buildup of fine material at one location. A similar directional pattern was noted in the ejection of fines from the approach slab.

PROGRESSION OF FAULTING

In 1968, a program was initiated to study the progression of faulting in various regions of the state. On selected sections, faulting was measured at 25 consecutive joints and averaged to obtain a faulting value for the project. Although the amount of displacement varies considerably from one joint to the next, 25 measurements were deemed indicative of the entire project. By periodically re-measuring the same joints, trends in faulting could be determined.

The sections selected covered all regions of the state where concrete pavements are placed. These included desert, coastal, valley and mountain areas. Pavement ages ranged from new to 13 years at time of initial measurement. One variable, joint spacing, included uniform 15 ft. spacing, staggered spacing of 13, 12, 18, 19 ft (and repeat), and an experimental section with spacings of 8, 5, 7 and 11 ft (and repeat). As other experimental features were constructed, additional test sections were established.

Figures B-1 through B-30 in Appendix B show plots of the faulting data for most sections being monitored. These graphs were included in a previous report (3) but have been updated to show faulting after 4 additional years of service. Several trends have now become evident, some of which were not recognized at the time of the previous report.

Faulting is shown to begin almost immediately after a pavement is opened to traffic (regardless of region) and increases with time, although the rates of increase may vary considerably. Those projects with the slowest increase are in the semi-arid regions of the state (Figures B-1, 2, 7, 11, 25). Those with the greater rates are in the mountain and coastal regions where more rainfall or equivalent snowfall occurs (Figures B-10, 12, 21, 26, 28, 30). The remainder of the projects are considered to be in the valley region and have rates of increased faulting that are generally in between the two extremes. One anomaly was found on one section in the semi-arid region. The pavement built over an existing PCC pavement indicated a significant increase in faulting at the last measurement. Two other sections on the same project (not overlays) show no significant change from previous measurements. The project will be watched more closely in the future to see if the increased rate of faulting continues.

Figures B-15 through B-22 show faulting of some experimental base and shoulder construction. The "control" listed in the figures refers to the standard constructed pavement of 8-9 inch thickness and shoulders of aggregate base covered by asphalt concrete. None of the shoulder or base treatments had any significant effect on faulting. Only the section where both an erosion resistant lean concrete base and a wedge of asphalt concrete was placed in the shoulder at the pavement base interface reduced the faulting rate (Figure B-21). The fact that any faulting at all has developed is disturbing since it was believed that the sources of fines had been eliminated. Because the project is located through coastal sand dunes, fine sand may be sifting through the joints and cracks. If surface fines are the source, sealing of the joints might have prevented the faulting.

The faulting of five experimental pavement sections is shown in Figures B-23 and B-24. Two of these sections are increasing in faulting at a rather alarming rate, especially in consideration of the very low volume of traffic for about the first 7 years of service. The sections with concrete base are performing surprisingly well considering there was no treatment to prevent movement of shoulder fines. Those with joint spacings of about 1/2 the normal length also show low faulting values, although for a given length of pavement, total amount of faulting would be almost as much as that of the control section.

Forming transverse joints by inserting plastic strips in the fresh concrete was expected to provide some benefits in the reduction of faulting by eliminating the reservoir left by sawing which can collect water and fines. However, Figures B-25 through B-29 do not indicate any significant advantage of inserts over sawed joints.

Figure B-30 shows faulting of sections with experimental shoulders. On portions of the project the outer shoulder was constructed full width with either asphalt or portland cement concrete which extended the full depth of the pavement concrete. As shown in the graph, both experimental shoulders reduced faulting significantly although the rate of faulting is still relatively high.

This study indicates that improved base design alone, or shoulder improvements only, will not solve the faulting problem. The base-slab interface should be completely protected from any source of loose fine material.

RECOMMENDATIONS

For new PCC pavement projects, it is recommended that design features include the following (see Figure 22):

1. An erosion resistant base.

Lean concrete and dense graded asphalt concrete have been found to be superior to most cement treated bases in this regard. (Another product being investigated for base is asphalt treated permeable material [ATPM]. This product consists of an open graded, no-fines aggregate with 1 1/2 to 2% asphalt. The ATPM could serve the dual purpose of providing drainage and a nonerodible base.)

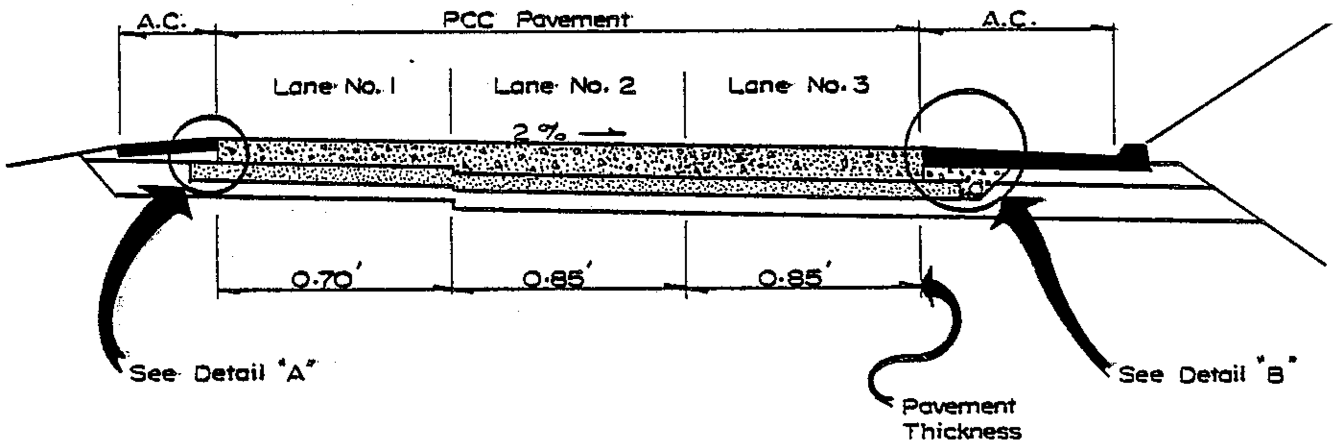
2. A drainage facility for the outside shoulder area adjacent to the slab.

The drainage facility should consist of slotted pipe covered with no-fines permeable material, preferably cement or asphalt treated, and filter fabric enclosing the permeable in areas adjacent to untreated material to avoid contamination of the permeable. Pipe outlets should be designed to provide for possible flushing in case the drain becomes plugged.

3. Consideration should be given to sealing all joints and placing filter fabric at the slab-base interface at the inside shoulder to provide additional protection from other possible sources of fine materials which could lead to faulting.

For pavements previously built without the above recommended protection, and on rehabilitation projects, the following measures are recommended:

TYPICAL PCC PAVEMENT DESIGN



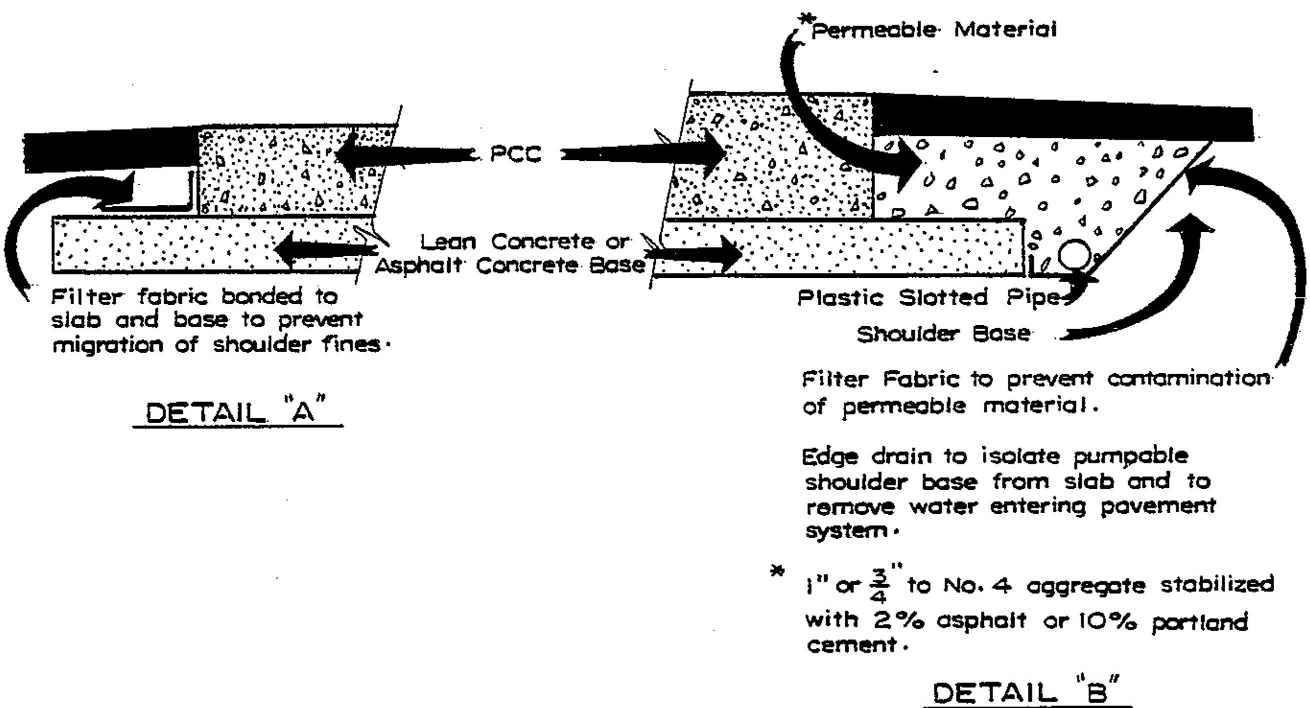


Figure 22

1. Construct a drainage facility as described by No. 2. This would serve to remove water and prevent the intrusion of any additional fines.

2. Immobilize fine materials already under the slab.

It has been found that, during the pumping action, fines may be ejected into the shoulder, possibly plugging the drainage system. Attempts to immobilize the fines have been made in the field by injecting a cement and pozzolan grout under the slabs, and in the laboratory with a chemical grout.

While this recommendation cannot yet be implemented, it is considered to be of vital importance. Work on this problem is under way and, hopefully, materials and procedures will be developed for this purpose in the near future.

REFERENCES

1. "California Pavement Faulting Study," a State of California report, M&R 635167-1, January 1970.

2. "Faulting of Portland Cement Concrete Pavements," a State of California report, M&R 635167-2, January 1972.

3. "Faulting of PCC Pavements," a State of California report, TL-5167-77-20, July 1977.

4. "Pavement Faulting Study. Investigation into the Causes of Pavement Faulting on the Georgia Interstate System," GDOT Research Project No. 7104, January 1975.

5. "California Trials With Lean Concrete Base (LCB)," a State of California report, TL-5167-3-75-37, October 1975.

6. "Compare In-Situ Strength of Asphalt Concrete Base (ACB) to Cement Treated Base (CTB)," a State of California report, TL-3110-1-74-17, December 1974.

7. Kapernick, J. W., "Equipment for Studying Pavement Joint Performance in the Laboratory," Journal of the PCA Research and Development Laboratories, 5, No. 2, May 1963.

8. "The Catskill-Cairo Experimental Rigid Pavement," A Five-Year Progress Report, James Bryden and Richard Phillips, Research Report 17, NYSDOT, November 1973.

APPENDIX A

SPECIFICATIONS FOR A PAVEMENT CYCLIC-LOAD SIMULATION MACHINE

1.0 General

This specification describes a fatigue rated (1×10^8 minimum cyclic life) closed-loop electro-hydraulic testing machine system that is to be used to apply cyclic loads to simulated pavement sections. This system shall have the capability of operating on load or stroke control modes, and shall be capable of exerting cyclic tension and compression forces of up to 15,000 pounds as shown in Figure 1.

It will be the responsibility of the successful bidder (contractor) to design and furnish a complete system that will fully comply with the performance requirements listed in the following paragraphs and Figure 1. Bids shall be accompanied by sufficient documentation to clearly indicate the conformance of the proposed design with these specifications. To insure continued parts and service availability, the contractor shall demonstrate that the manufacturer of each major subsystem component has produced several identical items and that the entire proposed system is composed of production model components.

The proposed system is to be used with a test bed and reaction frame that will be provided by the Transportation Laboratory. The test bed will consist of two full size pavement slabs and a shoulder section along with the required base and subbase. Loads are to be applied to each side of the pavement transverse joint to simulate an axle load moving from one pavement slab to the next. The load on the "approach" side of the joint is to be applied at a relatively slow rate followed by a sudden release. The load on the "leave" side of the joint will be applied rapidly and then slowly released. A typical loading sequence is illustrated in Figure 1. These cycles, separated by an interval of a few seconds, will be applied 24 hours a day. With this continuous testing, it is anticipated that the phenomenon known as pavement faulting will be induced in less than two months. However, the proposed system shall be designed for a minimum continuous operation period of 90 days without need for shutdown, maintenance, recalibrations or readjustments.

It is anticipated that the acceptance test of the proposed system will be verified in a universal testing machine or the reaction frame if completed. The Transportation Laboratory has a 1,000,000 lb (MTS Model 810) testing machine that may be used for this purpose.

The entire system - electronics, hydraulics, mechanical components, etc. shall be of proven long term fatigue resistant quality. When the system is energized it must be capable of continuous operation without maintenance or shutdown for 90 days and longer.

The system shall automatically shutdown for all malfunctions including electrical power interruption and shall not automatically restart. Restoration of interrupted electrical power shall not automatically restart electronic systems.

The contractor shall furnish all materials, equipment, labor and facilities to manufacture, test, and setup the acceptance testing of a fully operational system. The Transportation Laboratory will provide necessary electrical power supply, cooling water, and drain facilities and connection to the equipment. The contractor will provide checkout of the system as installed and instruction of Laboratory personnel who will be operating and maintaining the equipment.

2.0 Technical Characteristics

The system shall be comprised of three major subsystems; load actuation subsystem, a hydraulic power subsystem, and an electronic control subsystem.

2.1 Load Actuation Subsystem (Two Each Required)

The two 15,000 pounds capacity hydraulic actuators shall be capable of applying a force and time history to conform with the pulse curves in Figure 1 and with actuator movements of up to .100 inches. The system shall be stable in all operating modes per these specifications and Figure 1. The actuators shall be designed to withstand heavy sideloads. The configuration of each actuator subsystem shall be as follows:

A. Double-ended one piece piston rod, double-acting, and designed for 3000 psi operating pressure and a stroke of 4 inches minimum.

B. Assembly shall be complete with integrally mounted servo-valves and manifolding, close coupled accumulator, in-line 10 micron filter, full stroke LVDT, fully enclosed and concentrically mounted within the hollow piston rod.

C. Manifolding shall be bolted directly to the actuator and shall provide adjustable remote controlled low pressure, fail-safe and slow turn-on/slow turn-off functions to assure transient-free operation between high and low pressure conditions.

D. Servovalves shall have external pilot pressure provision. If dual servovalves are needed per actuator to meet response time shown in Figure 1, one servovalve shall have manual shutoff provision. Pressure accumulator shall have 1 quart minimum capacity.

E. Both ends of actuators shall be fitted with swivels having adjustable preload feature, and spiral washers to eliminate backlash and fatigue resistant connections throughout.

F. Actuators are intended for vertical mounting, rod end down.

G. Actuator rod seals shall be three stage, an outer scraper ring to prevent external contamination by the dust and grit generated in the test area, and a two-stage inner seal with positive oil flow between assuring proper lubrication during short stroke operation.

H. 15,000 pound fatigue resistant load cell (1 x 10^8 cyclic life at rated fatigue load) shall be installed at rod end behind swivel. Load cell accuracy with DC conditioner shall be within 1 percent of reading for loads between 10 percent and 50 percent of calibrated range and within 0.5 percent of range for loads between 50 percent and 100 percent of calibrated range.

I. The load cells shall be of the electrical resistance strain gage type and have a minimum overload capacity of 150 percent of the actuator's stall force. The load cells shall be supplied with a calibration traceable to the National Bureau of Standards. The load signal shall be accurate to within 1/2 percent of the operating range. The load cells shall have female threads concentrically in their lower end for attachment of specimen grips, etc. These threads shall be of the same size as those in the actuator rod.

2.2 Hydraulic Power Supply Subsystem

The hydraulic power supply shall have a minimum capacity of 10 gpm and sufficient to supply adequate fluid flow to the actuation subsystem to operate in accordance with the performance curves in enclosure, Figure 1, and with rod movements of up to 0.100 inches. The system pressure shall be 3000 psi continuous duty. The hydraulic power supply subsystem shall have local and remote start. Filtration to be at least 3 micron on the output. The main pressure shall be adjustable with a separate adjustable safety relief valve. The system shall have a high/low pressure solenoid and a properly sized pressure line accumulator. Fluid level and fluid temp switches for failsafe circuit shall be provided. The pump shall be a positive displacement type driven by a drip-proof 460 volt, three phase 60 Hz motor. The motor shall have overload protection. The hydraulic power supply shall have a heat exchanger with the following oil cooling provisions:

A. A water-cooled heat exchanger shall be supplied.

B. A water-saver valve will be included to reduce water demand according to oil temperature.

C. The oil temperature shall be maintained between 100-120°F.

D. The noise rating shall be 74 dBA or less at 3 feet.

The sound level for any other location shall not exceed those values set forth in California Administrative Code Title 8, Part 1, Chapter 4, Article 105, Standards for Occupational Noise Exposure. A 460 volt, 3 phase, 60 Hz motor starter shall be an integral part of the hydraulic power supply. A hose set shall be supplied, 25 feet in length, minimum.

2.3 Electronic Control Subsystem

The electronic control subsystem components shall be grouped in a vertical standard 19 inch rack mounting console. The console shall be on casters, freestanding, approximately 73 inches in height and conforming to RETMA-type rack with standard EIA hole spacing or Unistrut type construction.

2.3.1 One master system Control Unit shall provide control of system hydraulic and instrument power and include the following features:

A. 110 volt power on-off.

B. Remote start/stop of Hydraulic Power Supply.

C. Hydraulic interlock to automatically shut down hydraulic pressure in response to abnormal control circuit or abnormal hydraulic power supply conditions.

D. On/off, hi/low pressure control of actuator assemblies.

E. Program run/stop.

F. Program event counting, and pre-set count program stop. Count capacity 999,990.

An end-of-count indication shall be provided and the cyclic function stopped when the cycle counter terminates the test. Counter must retain and display count after power loss.

2.3.2 Two Servo Controllers shall provide for closed-loop control of the test operation, with the following control modes:

A. Control based on load as sensed by the load cell.

B. Control based on stroke as sensed by the actuator LVDT.

Each Controller shall have at least two full-scale operating ranges to include 10% and 100% of capacity.

A separate transducer conditioner/amplifier shall be provided for each mode of control. An output from each conditioner/amplifier of plus or minus ten volts DC full-scale for each operating range shall be provided for driving external indicating or recording devices.

The control system shall include provision for use of an external DC signal (as from an analog computer or tape record signal) as the control input signal.

An individual level adjustment for each mode shall be provided on the control panel applicable to each control mode, adjustable from 0 to 100% of the control range.

The two (2) Servo Controllers shall include at least the following features:

A. High level input signals (plus or minus 10 volt full scale) and high level summing to minimize drift effects.

B. Variable set point or static level control.

C. Gain control for adjusting system response.

D. Error detector at summing junction to activate system fail-safe functions.

E. Adjustable limit detector to monitor either transducer signal for upper and lower limits to activate system failsafe functions.

F. Valve amplifier to drive single or dual servovalves.

G. Dither oscillator with adjustable amplitude.

H. An AC Transducer Conditioner with the following features:

1. For use with resistive or reactive transducers having sensitivities from 1 mv/volt to 1100 mv/volt.

2. Calibrated constant amplitude AC transducer excitation.

3. High level output (plus/minus 10 volt full scale).

4. Plus/minus 0.5 percent output linearity.

5. Zero suppression from 0 to plus/minus 100 percent.

I. A DC Transducer Conditioner with following features:

1. For use with resistive transducers having sensitivities from 1 mv/volt to 10 mv/volt.

2. Self-contained variable DC excitation supply.

3. Dual range (X 1 and X 10) operation with high-level output (plus/minus 10 volt full scale) on both signals.

4. High rejection of common mode signals.

5. RF Filtering in primary gain stage to reduce susceptibility to external transients.

6. Zero suppression from 0 to plus/minus 100 percent.

2.3.3 Two channel outputs (see Figure 1) shall be provided by a Dual Channel Digital Function Generator or two Generators. The outputs (shown in Figure 1) shall be independently programmed for each channel. The phase and timing relationship between the two channels shall be selectable by front panel start and break point switches. A selectable crystal controlled digital time base shall allow operation over a range of 0.0005 to 30,000 seconds for a single output waveform. The generator time-load pattern shall conform to the following specifications as shown in Figure 1:

1. Two (2) output channels ($\pm$10V).

2. Ramp period adjustable from 0.015 - 30,000 seconds for each output.

3. Time delay between cyclic pulse sequence variable from 0 to 11 seconds.

4. Overlap between pulses of Channel 1 and 2 continuously variable from 0 to 100%.

In addition, the programmed waveform shall be digital with a minimum of 1024 steps with a minimum 10-bit resolution.

2.3.4 A minimum 3-1/2 digit readout shall be provided to display the test parameters of load and stroke. The readout shall be front panel selectable to read test parameters from either actuator 1 or 2. It should also hold and display maximum/minimum peak cyclic parameters and shall have digital memory to store and display the extreme maximum and minimum values of the input voltage waveform.

The complete set of system cables shall be a minimum of 30 feet in length.

3.0 Manuals, Delivery, Acceptance Testing, Payment, Warranty.

3.1 Two sets of operation and maintenance manuals shall be provided. Manuals shall include detailed instructions for operation, maintenance and trouble-shooting for the entire system. Two sets of drawings and electrical schematics shall be provided.

3.2 Delivery

Delivery of the system for acceptance testing shall be within 150 days after purchase order is received by the successful bidder.

3.3 Late Delivery

In the event that delivery of all equipment is not completed within the 150 days the State may exercise the discretionary power of cancelling the contract.

3.4 Acceptance Testing

An acceptance test shall consist of successful continuous operation at a typical cyclic load pattern as shown in Figure 1, for a period of 30 days. Three-day services of a field engineer to setup and checkout the system for acceptance testing shall be provided. The engineer shall provide instruction in the operation and maintenance of the system, during a period of at least 8 hours during the 3-day period. Should the field engineer require more than the 3-days setforth above, it shall also be at the vendor's expense.

Should the system fail to conform to any of the requirements setforth in the specifications or fail in any manner during the 30-day acceptance period the vendor shall correct the problem within 10 calendar days at his expense. The 30-day acceptance period will restart after the vendor's rectification. Should the system again fail the same conditions for correction will apply until a satisfactory 30 day acceptance test is achieved.

3.5 Payment

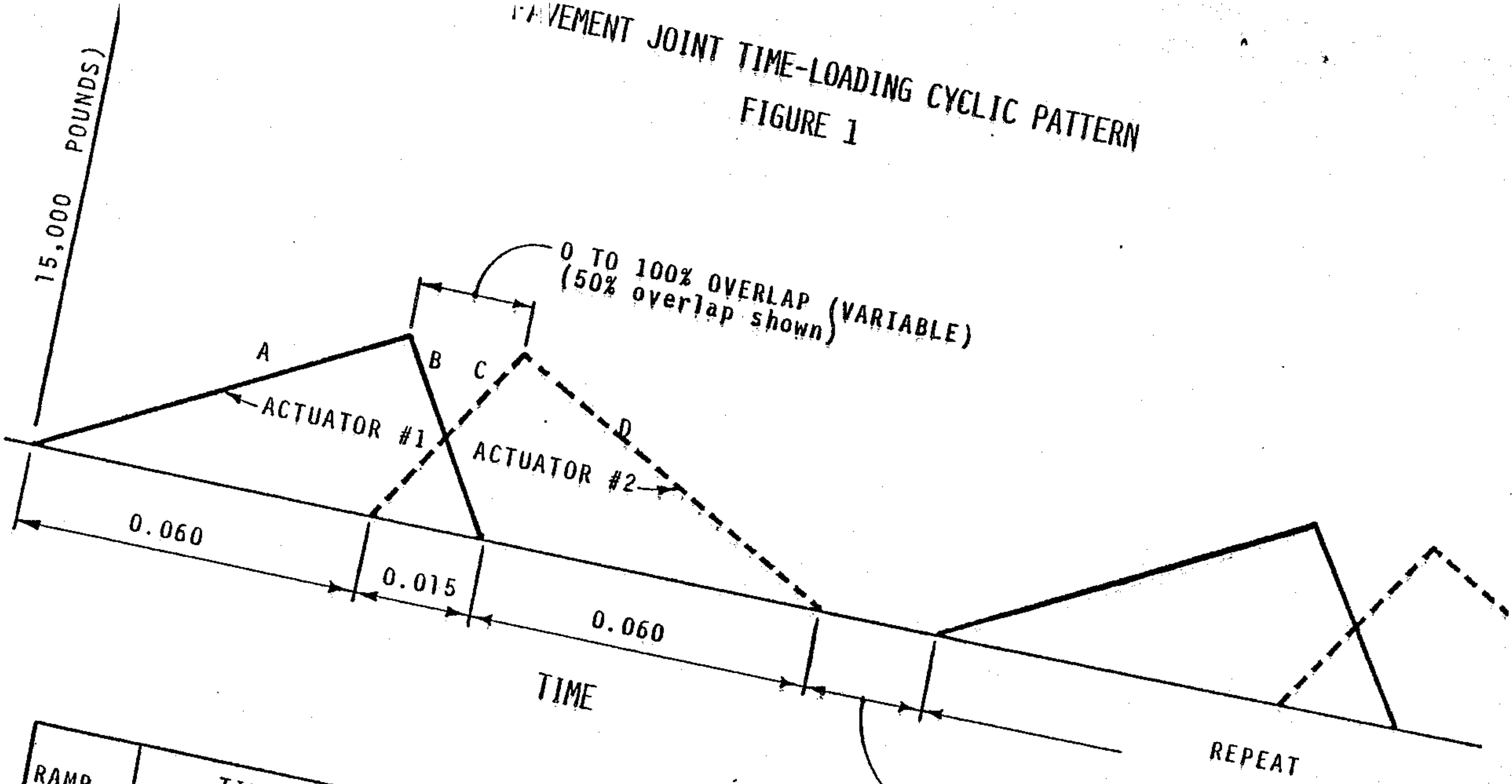
A initial payment of 80% of the contract price will be made upon delivery of the system to the Transportation Laboratory, 5900 Folsom Boulevard, Sacramento, California. Remainder of the payment will be made upon successful completion of the 30-day acceptance testing period.

3.6 Warranty

Upon successful completion of the acceptance period, the system shall be warranted for one-year to be functionally trouble-free and to be free from defects in material and workmanship. Any servicing or adjustments resulting from warranty service shall be at the vendor's expense and performed on State premises.

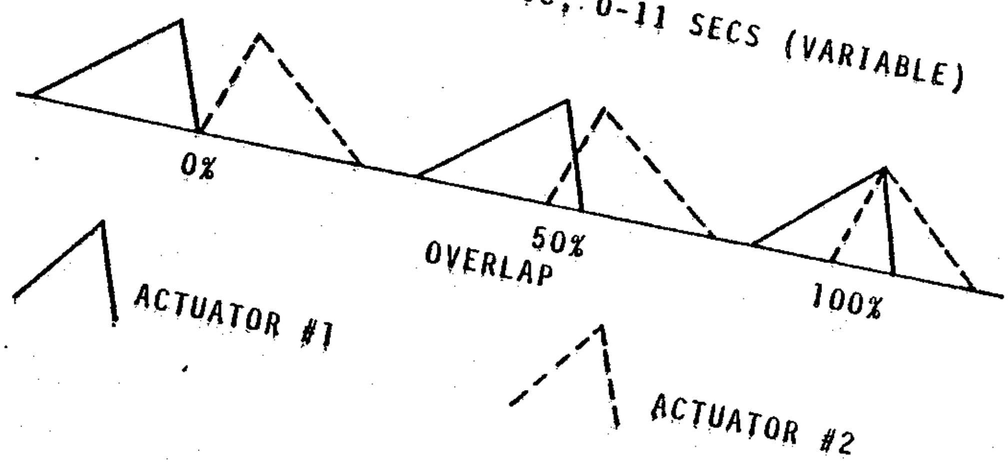
PAVEMENT JOINT TIME-LOADING CYCLIC PATTERN

FIGURE 1

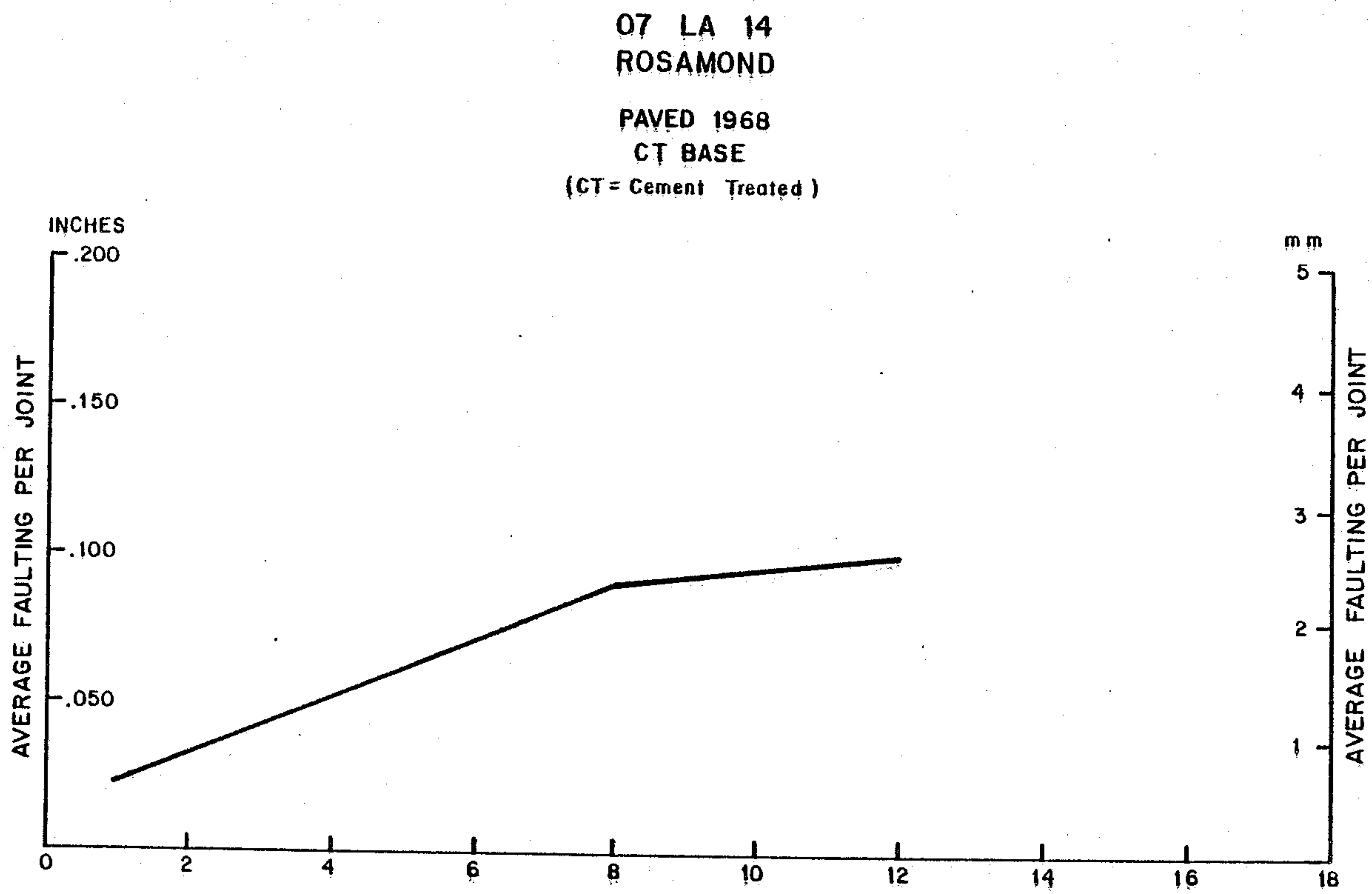


RAMP	TIME (SECONDS)	
	TYPICAL	VARIABLE
A	.060	.015 - 30,000
B	.015	.015 - 30,000
C	.015	.015 - 30,000
D	.060	.015 - 30,000

January 7, 1977



APPENDIX B

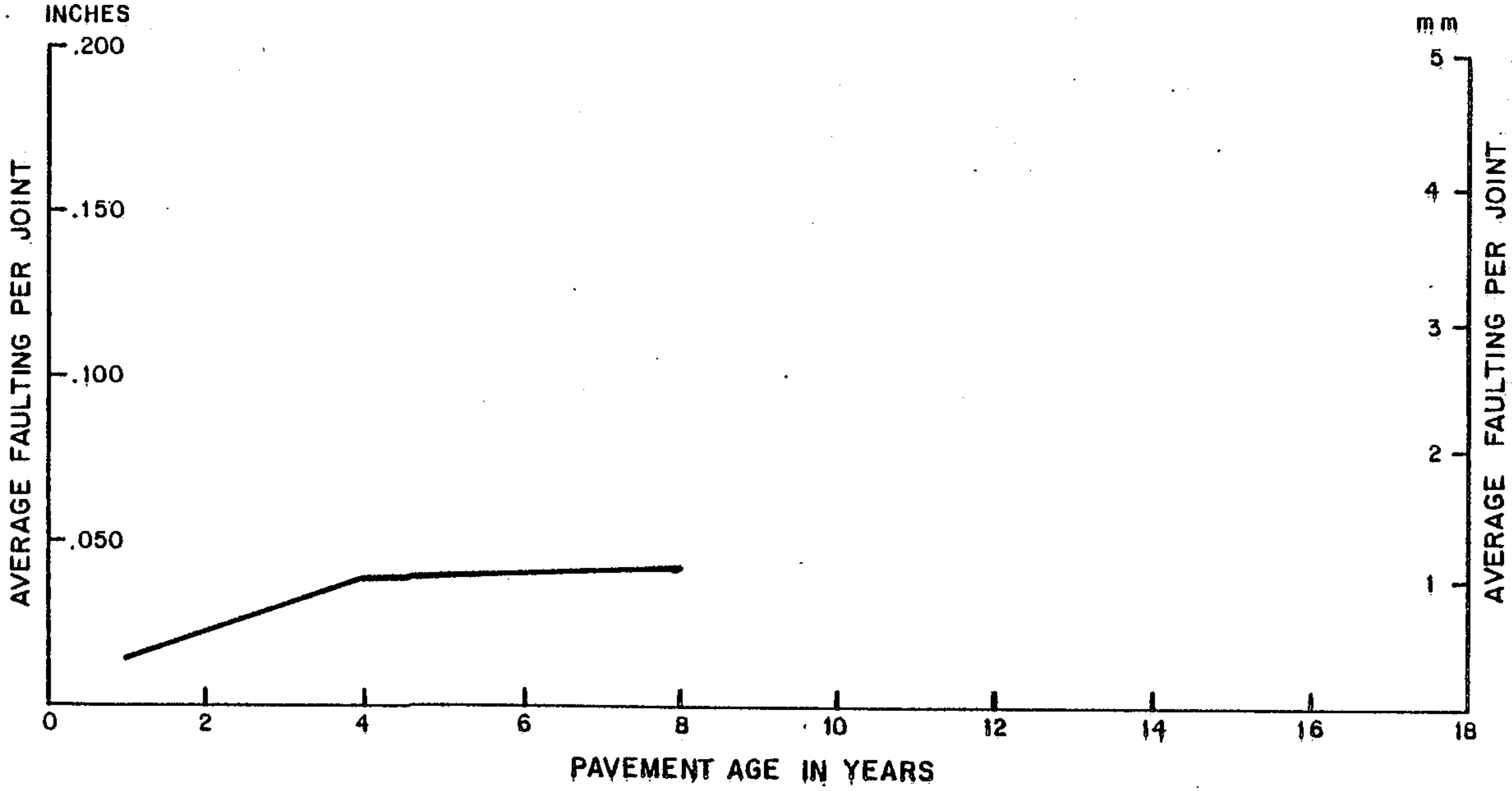


FAULTING TREND LINE

Figure B-1

11 Riv 10
INDIO

PAVED 1972
CT BASE

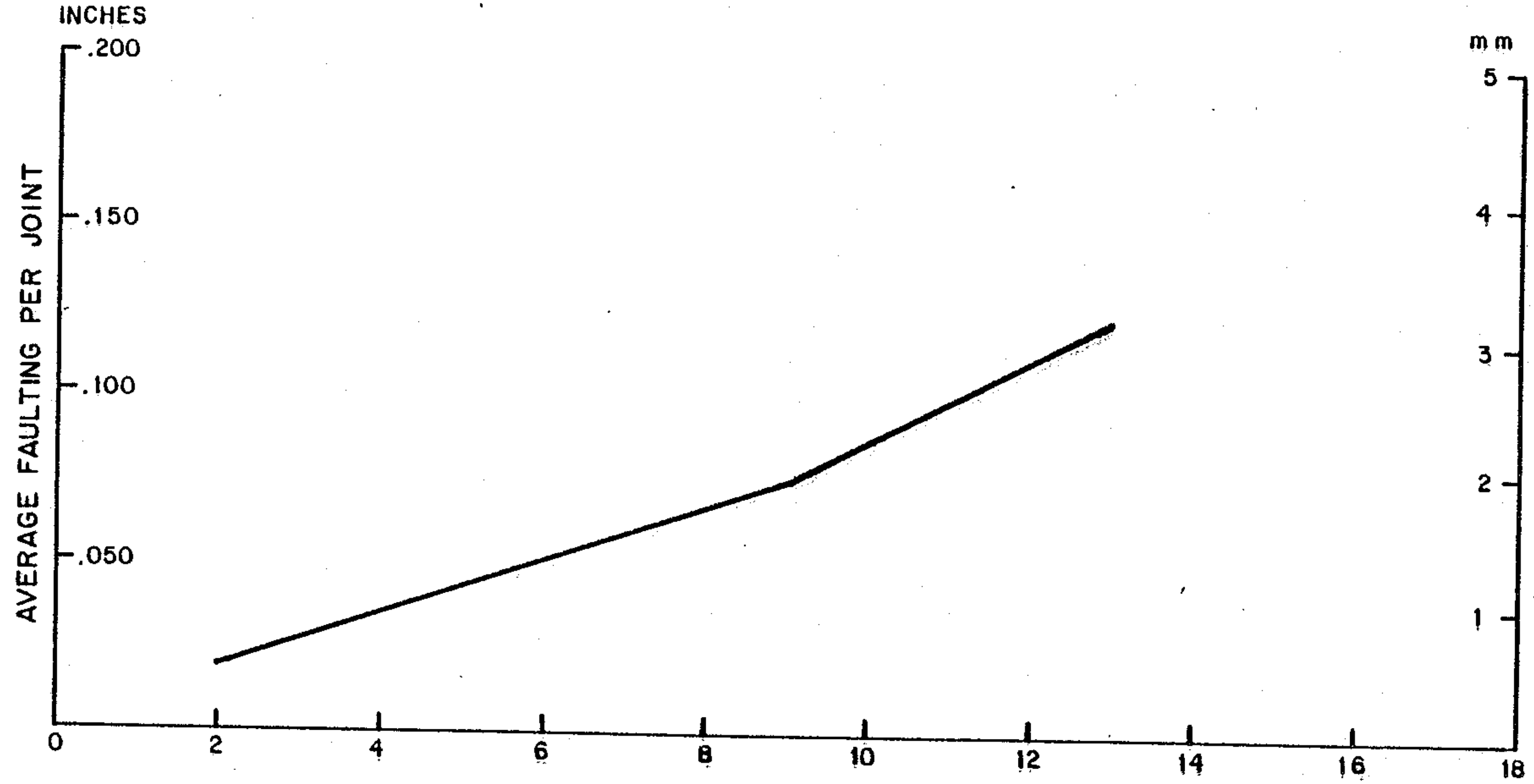


FAULTING TREND LINE

Figure B-2

02 Sha 5
REDDING

PAVED 1967
AC BASE
(AC = Asphalt Concrete)

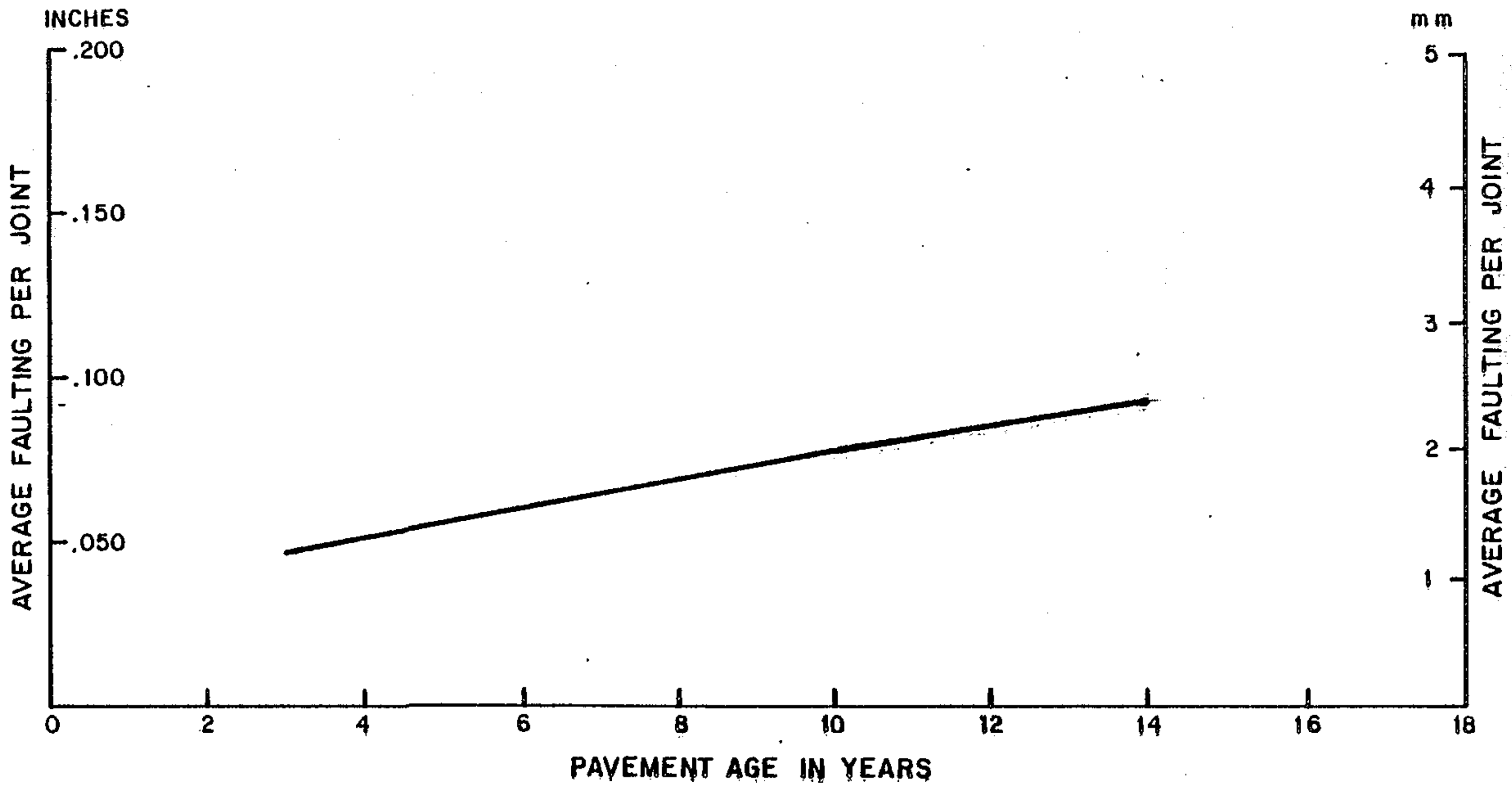


FAULTING TREND LINE

Figure B-3

10 Mer 5
GUSTINE

PAVED 1966
CT BASE

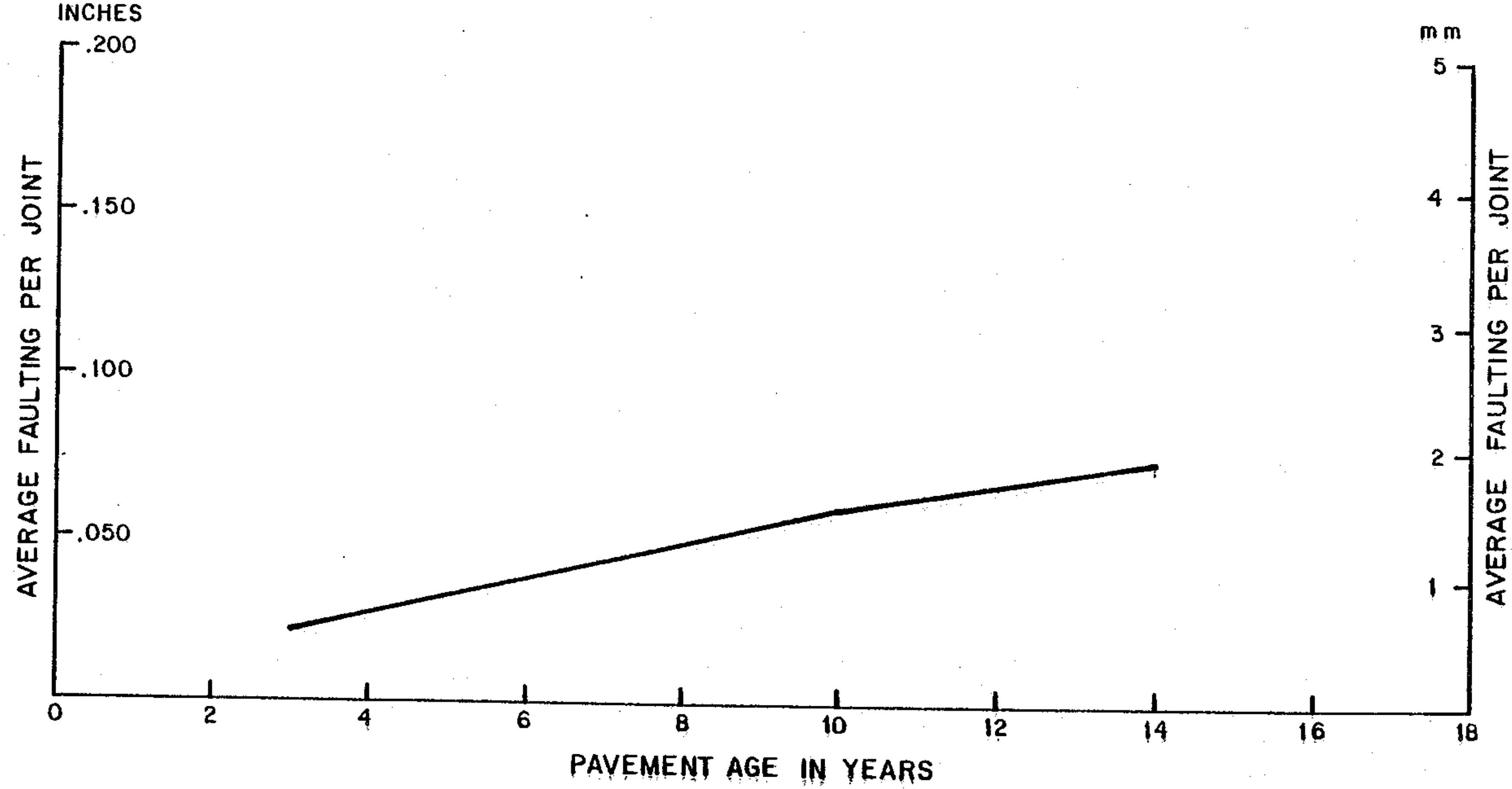


FAULTING TREND LINE

Figure B-4

10 SJ 580
VERNALIS

PAVED 1966
CT BASE

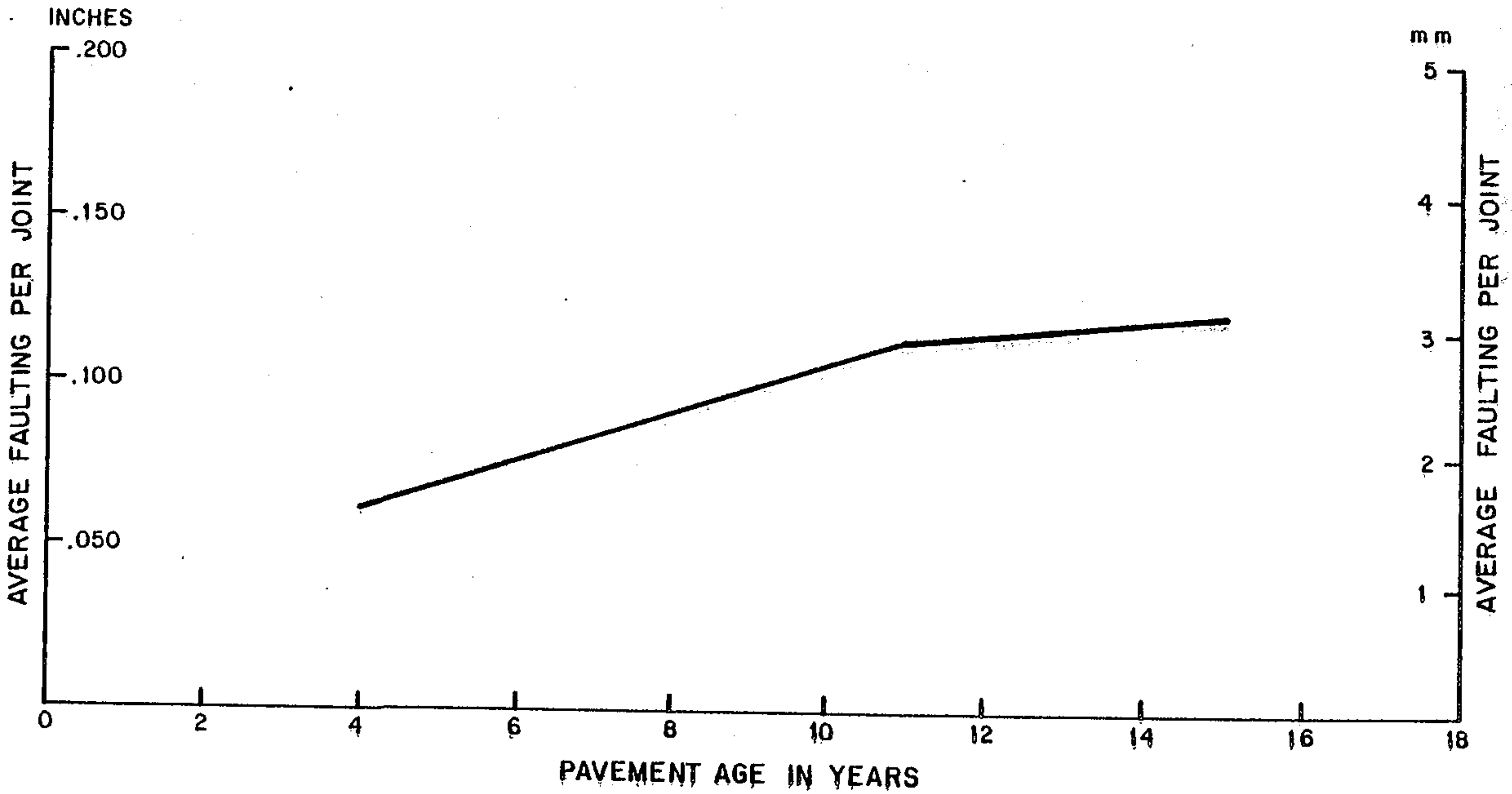


FAULTING TREND LINE

Figure B-5

10 Mer 152
PACHECO PASS

PAVED 1965
CT BASE

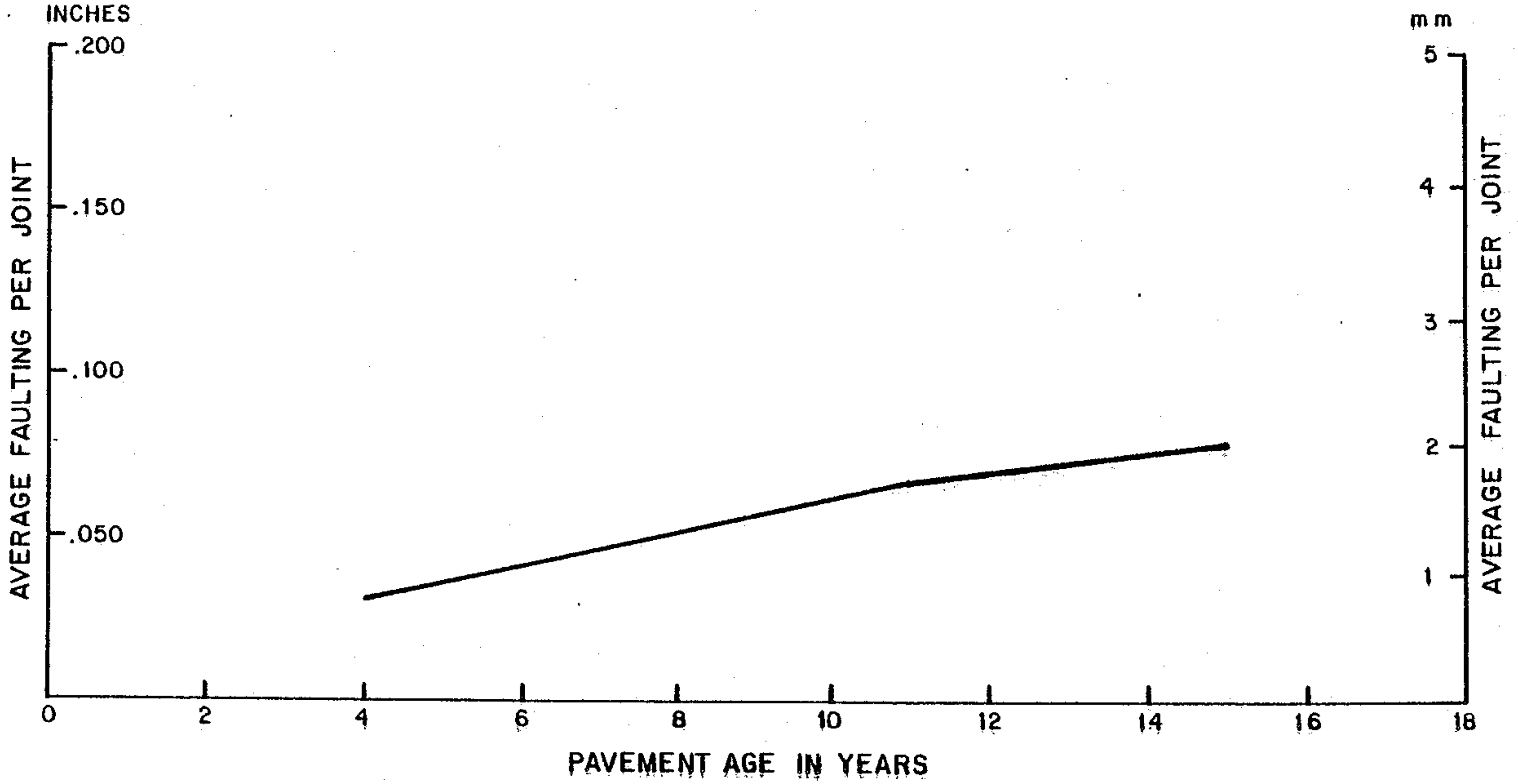


FAULTING TREND LINE

Figure B-6

08 SBd 15
CAJON PASS

PAVED 1965
CT BASE

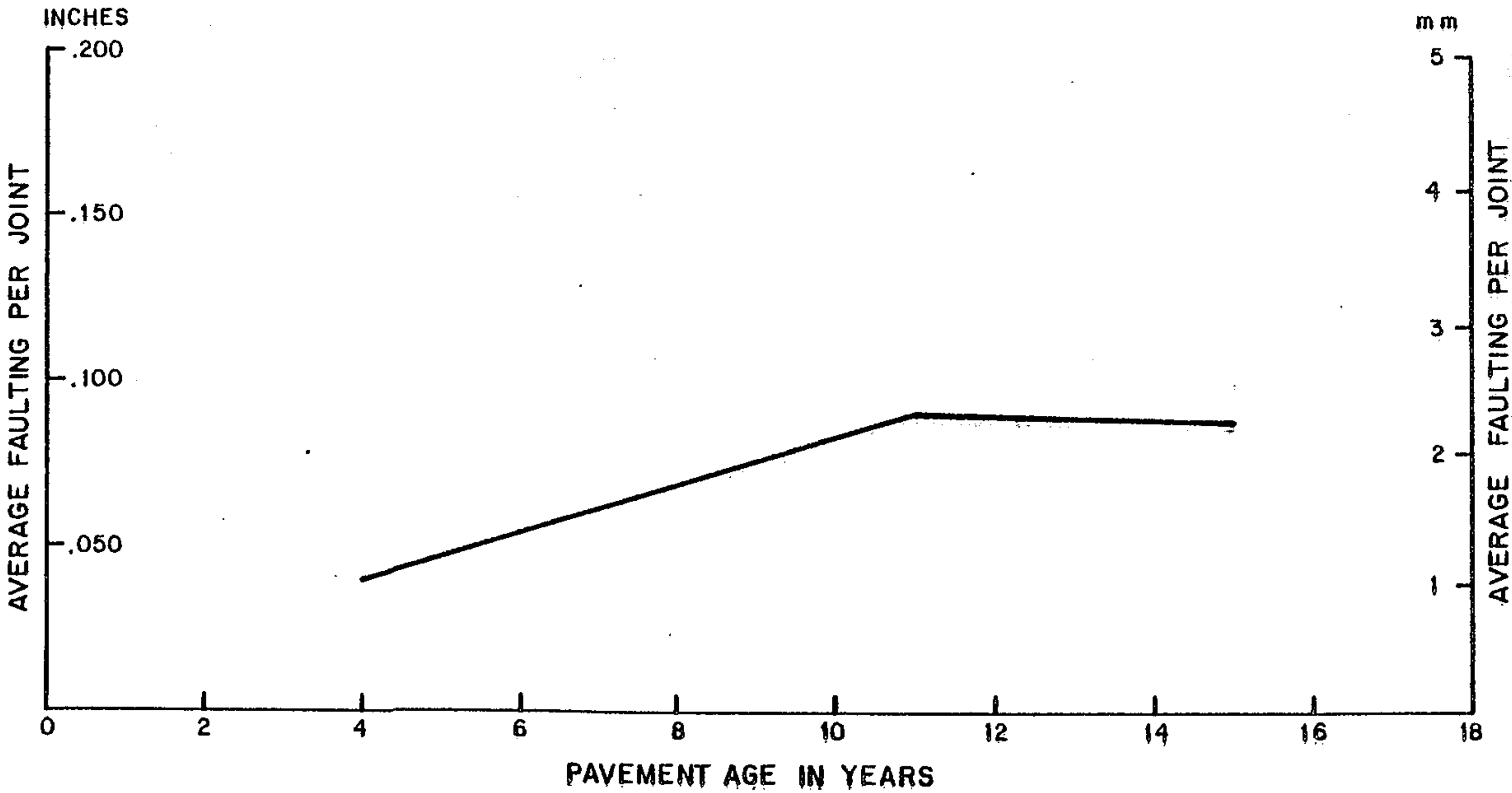


FAULTING TREND LINE

Figure B-7

09 Ker 58
TEHACHAPI WB

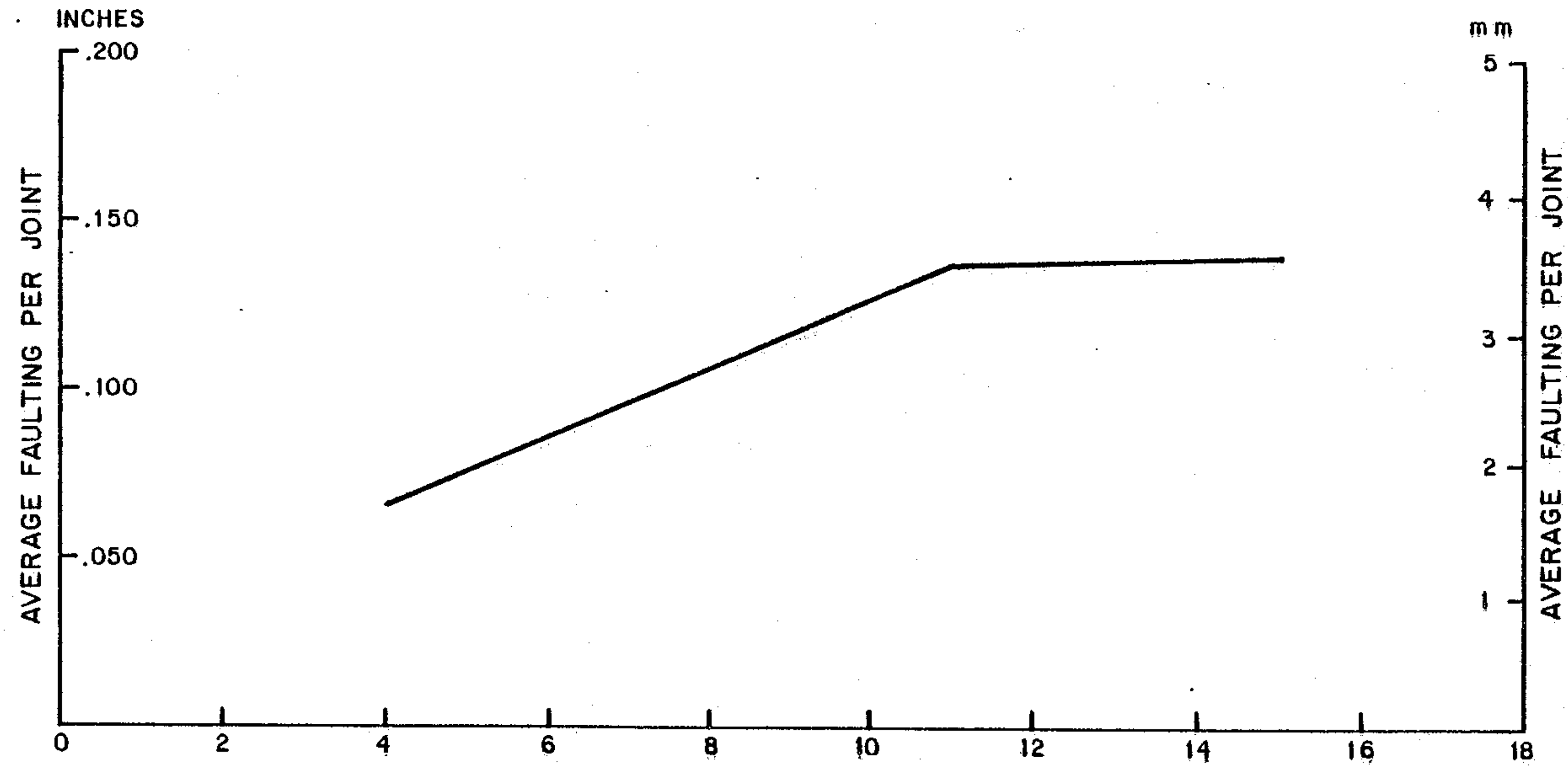
PAVED 1965
AC BASE



FAULTING TREND LINE
Figure B-8

09 Ker 58
TEHACHAPI EB

PAVED 1965
CT BASE



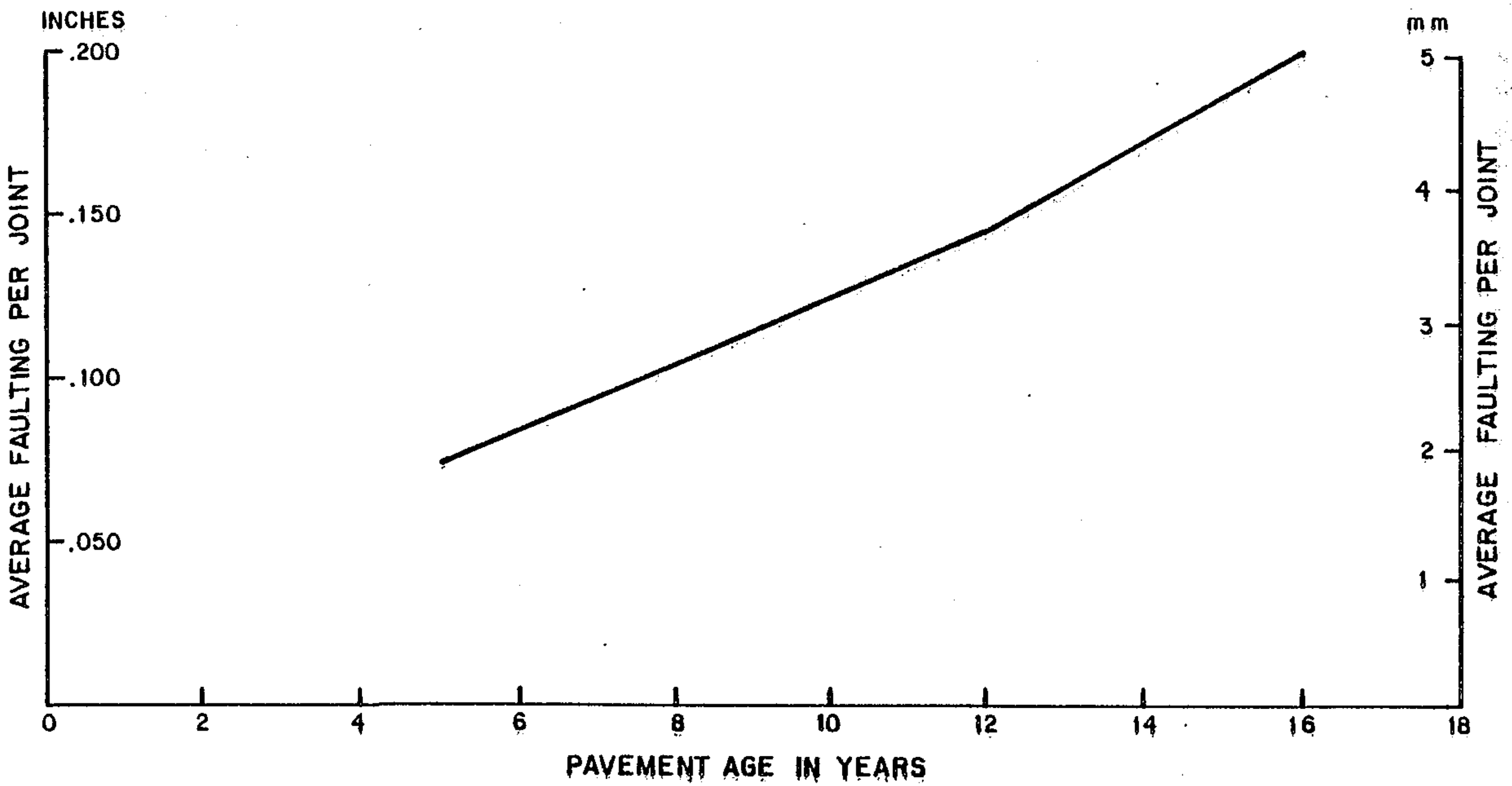
PAVEMENT AGE IN YEARS

FAULTING TREND LINE

Figure B-9

O2 Sis 5
MT SHASTA

PAVED 1964
CT BASE

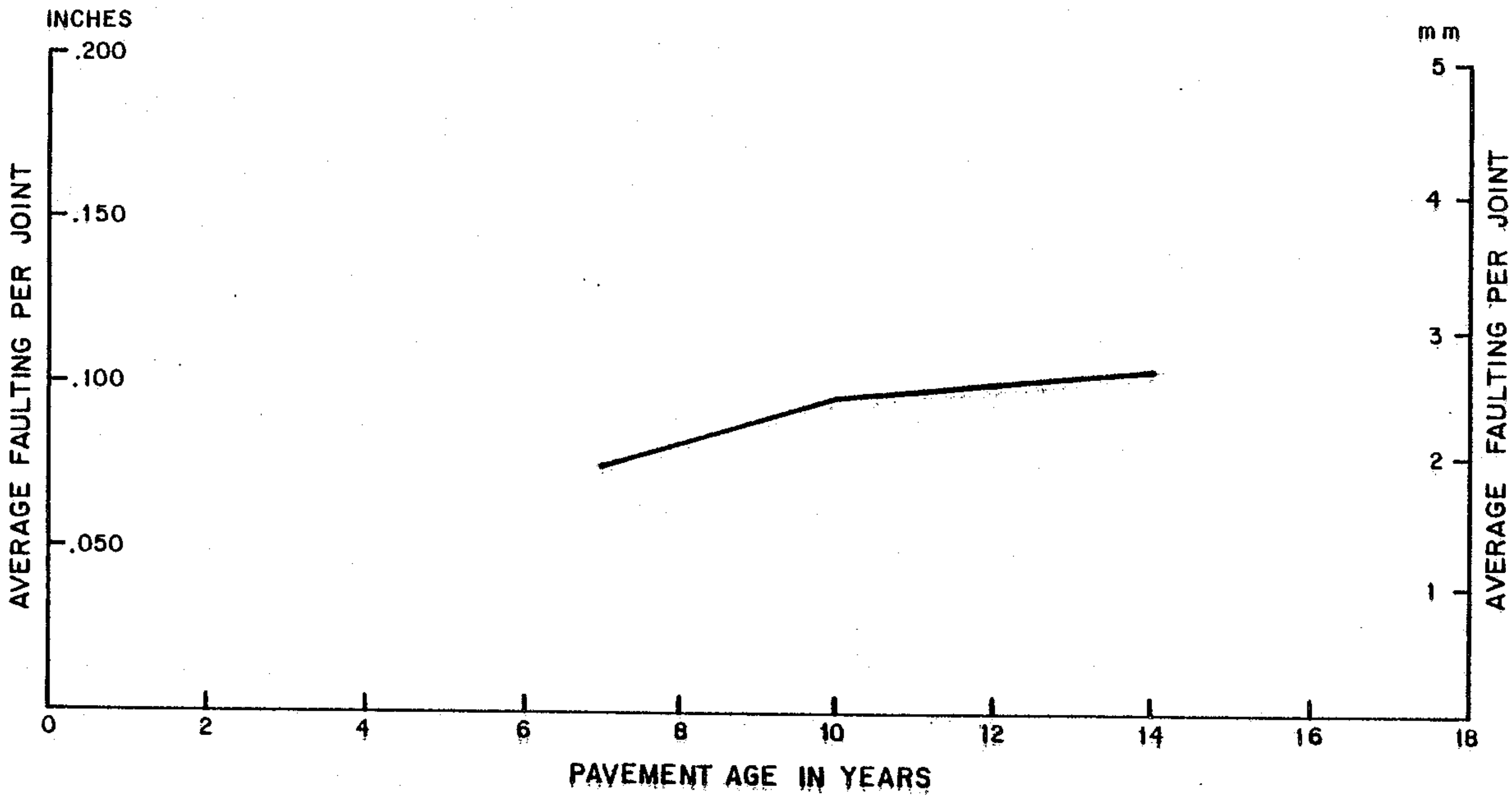


FAULTING TREND LINE

Figure B-10

08 Riv 10
CABAZON

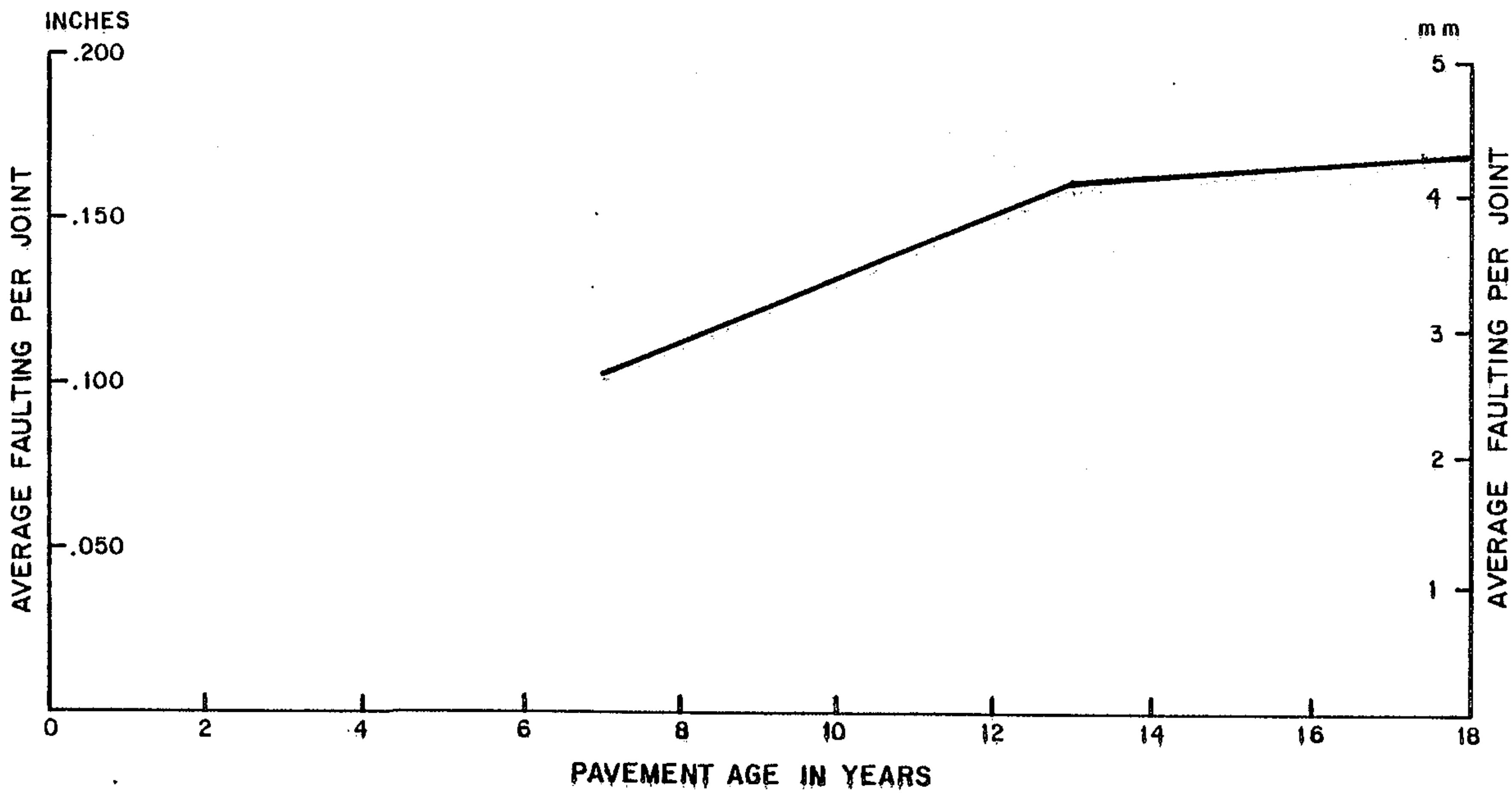
PAVED 1966
CT BASE



FAULTING TREND LINE
Figure B-11

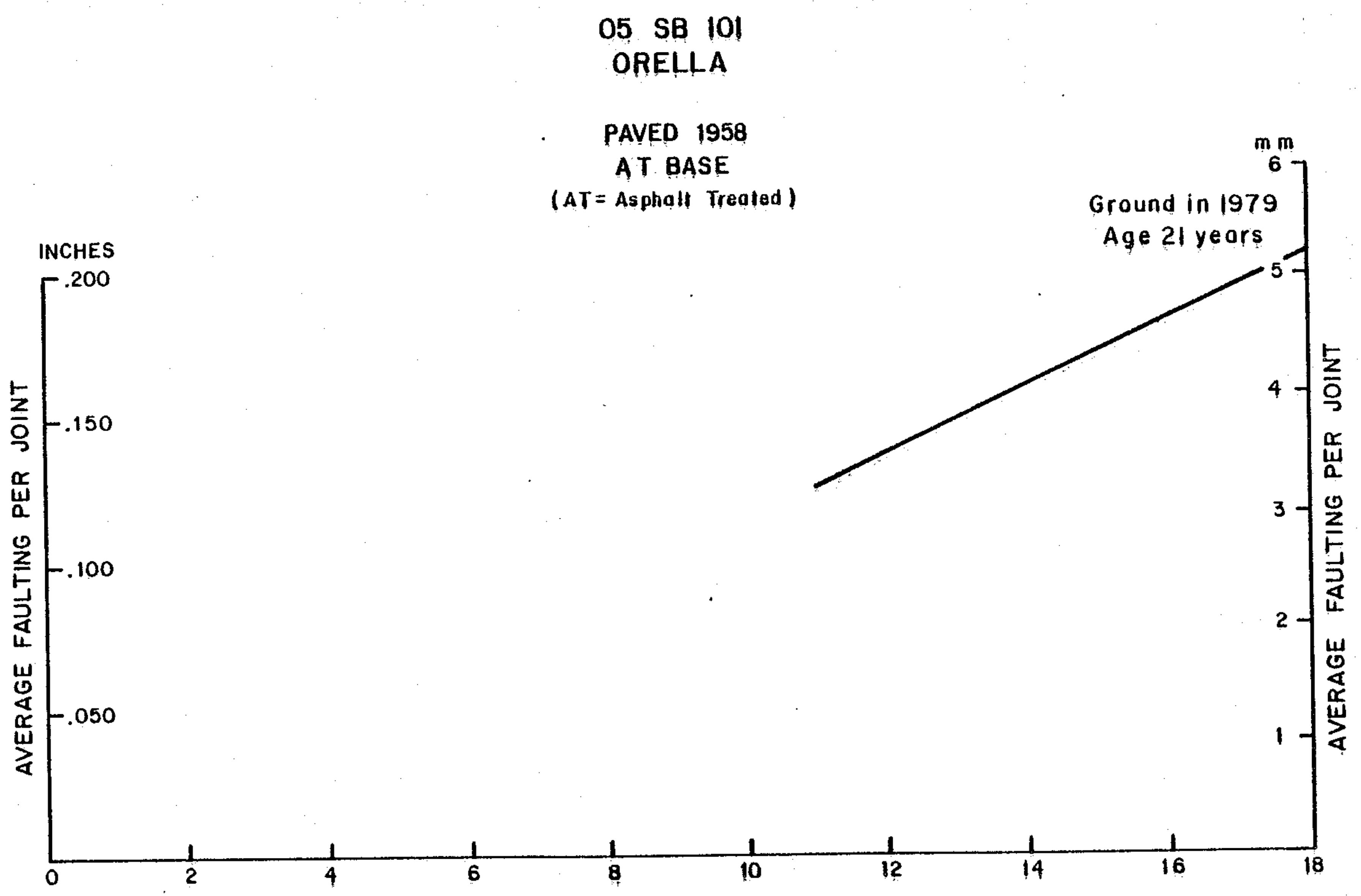
03 Nov 80
YUBA GAP

PAVED 1962
CT BASE



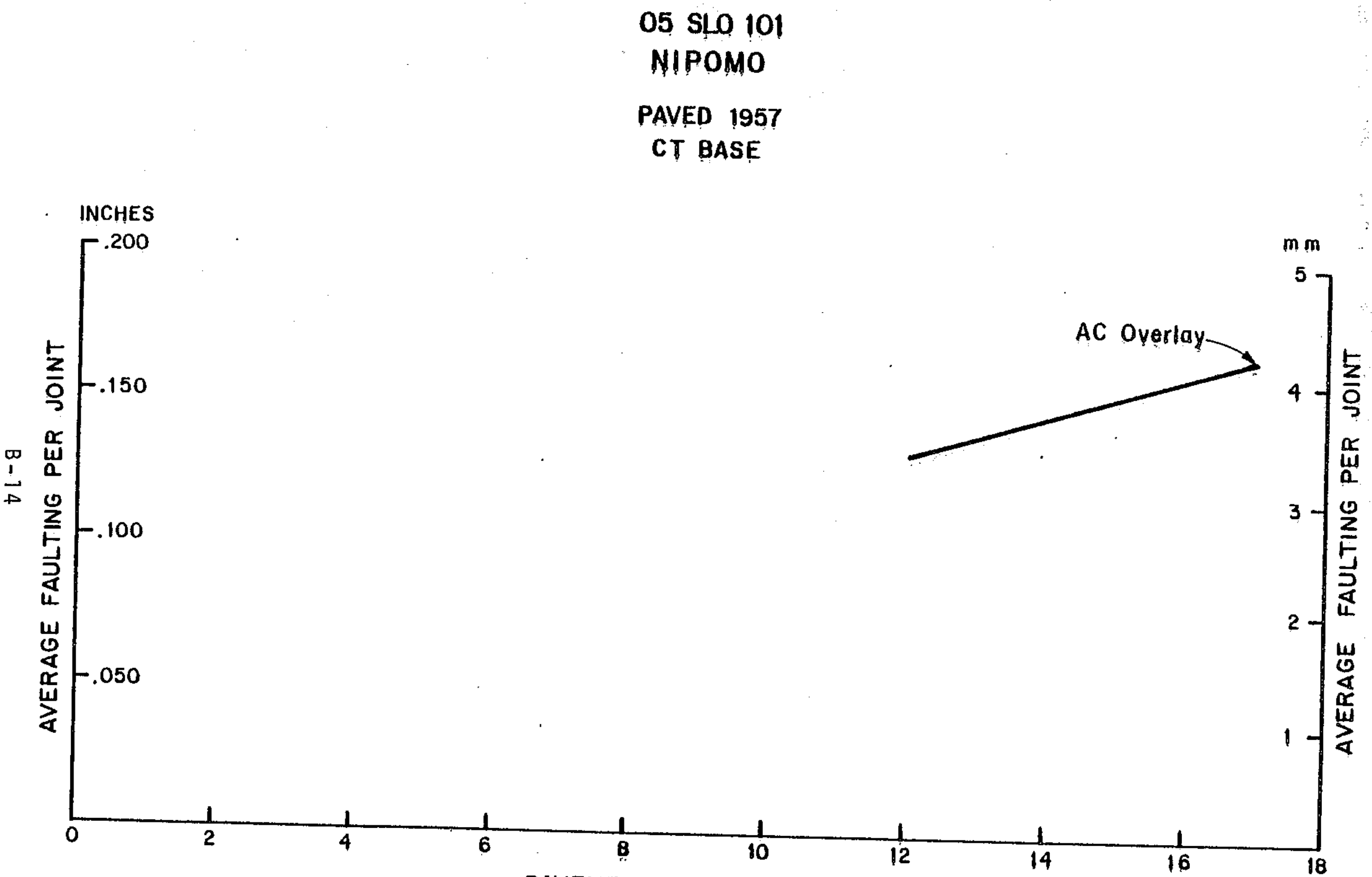
FAULTING TREND LINE

Figure B-12



FAULTING TREND LINE

Figure B-13

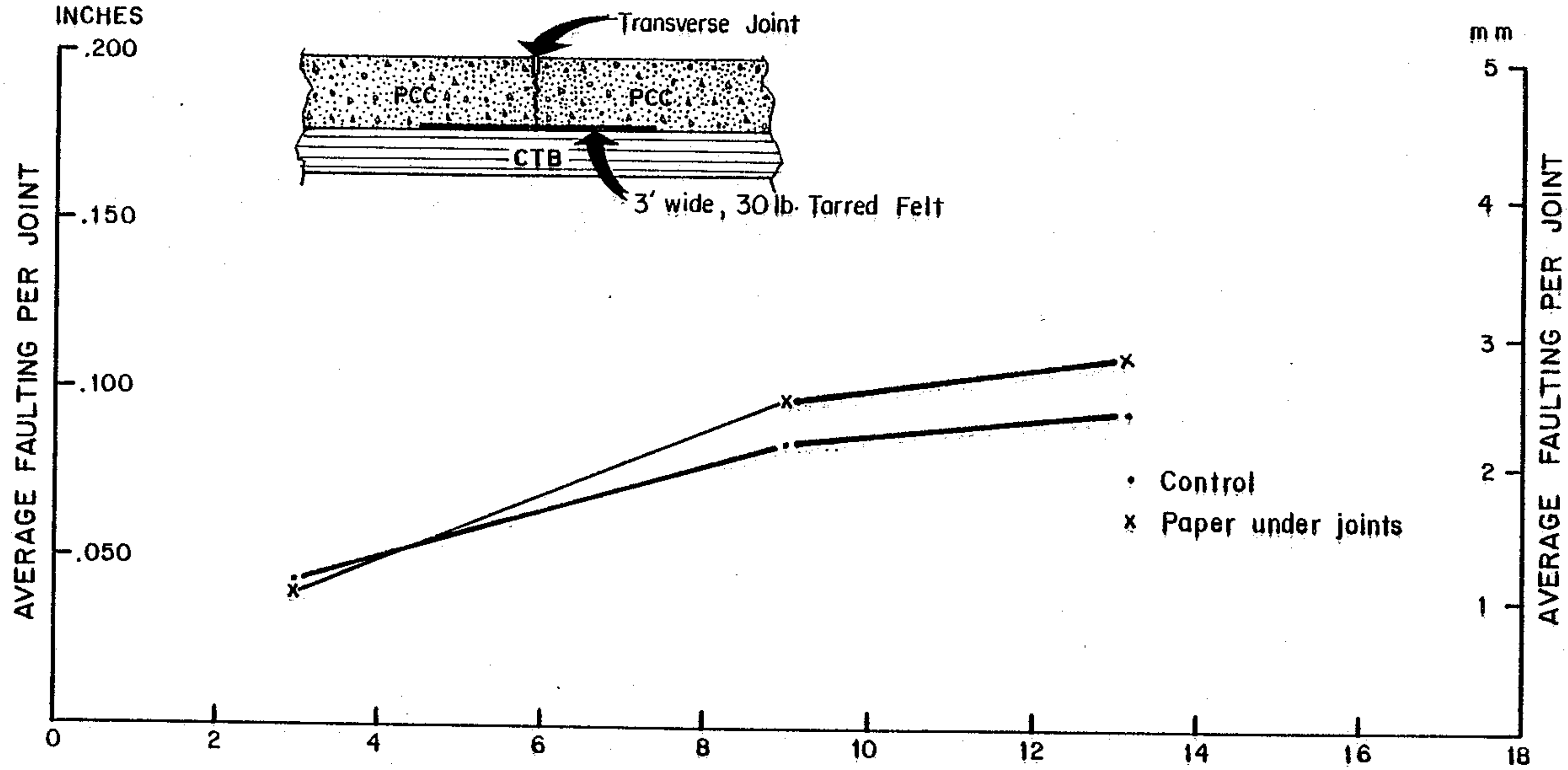


FAULTING TREND LINE

Figure B-14

04 Ala 680
SUNOL

PAVED 1967
CT BASE

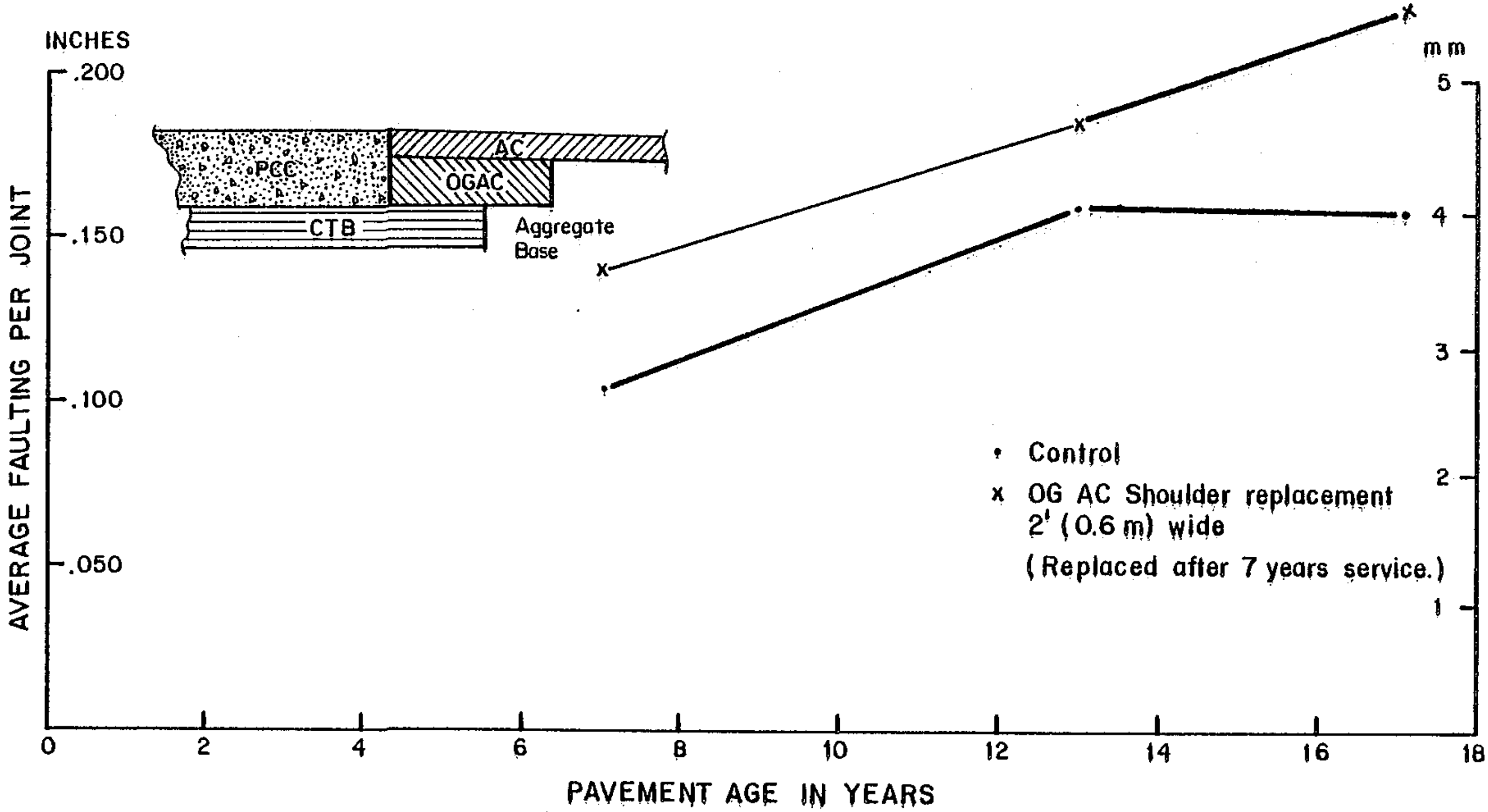


FAULTING TREND LINE

Figure B-15

10 Sol 80
VACAVILLE EB

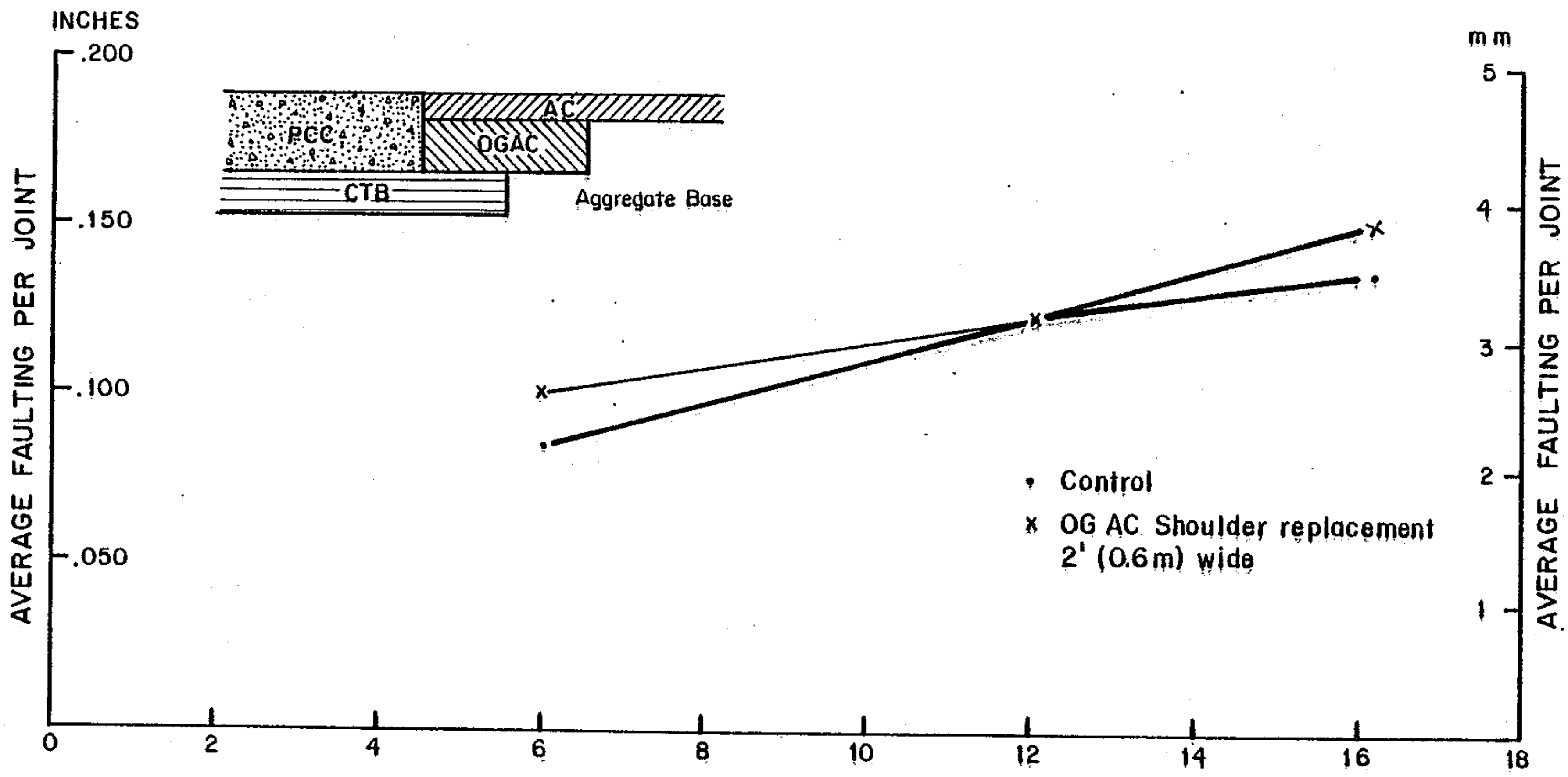
PAVED 1963
CT BASE



FAULTING TREND LINE
Figure B-16

10 Sol 80
VACAVILLE WB

PAVED 1964
CT BASE

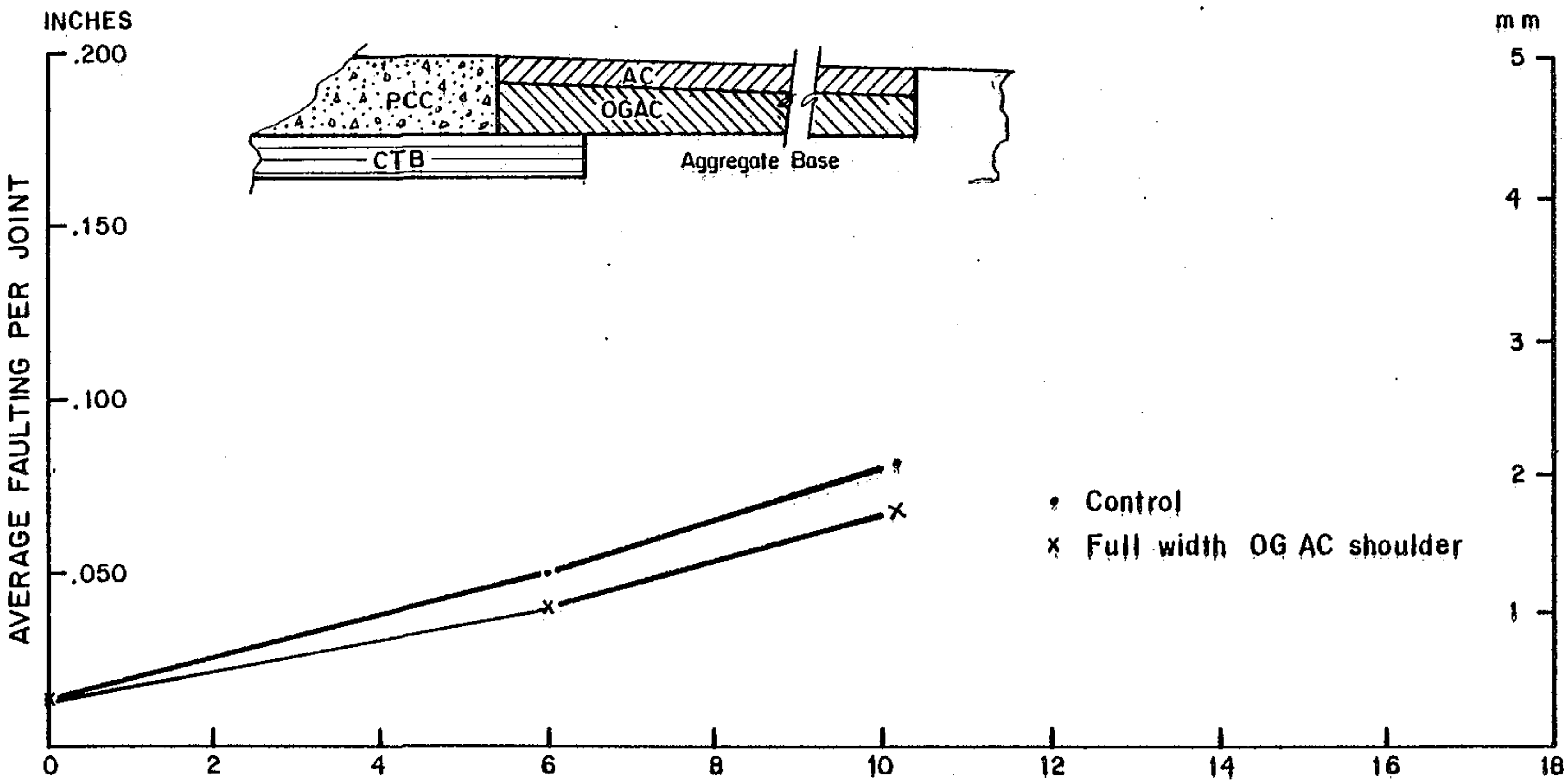


FAULTING TREND LINE

Figure B-17

03 Col 5
WILLOWS

PAVED 1970
CT BASE

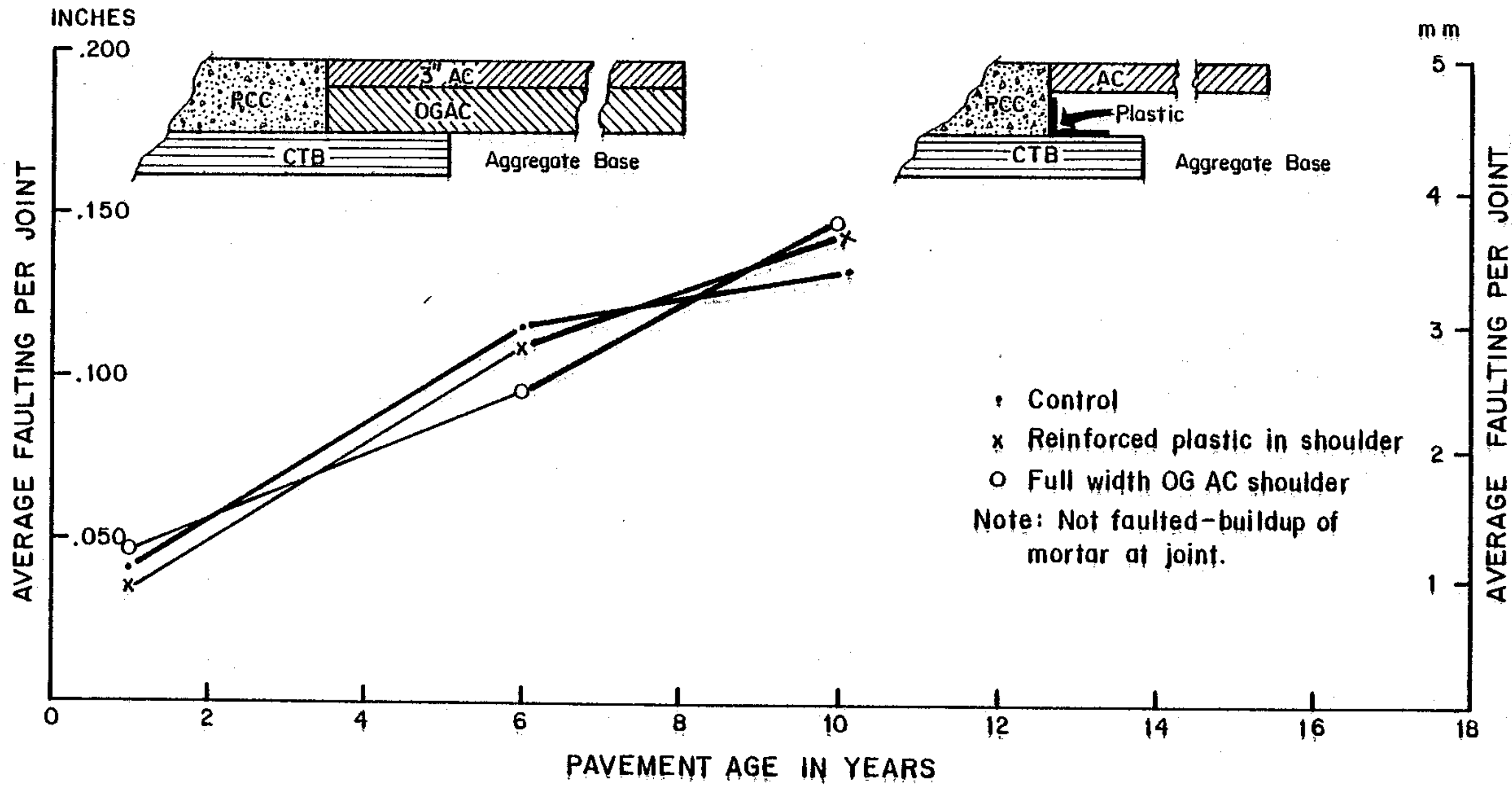


FAULTING TREND LINE

Figure B-18

10 Sta 99
SALIDA

PAVED 1970
CT BASE

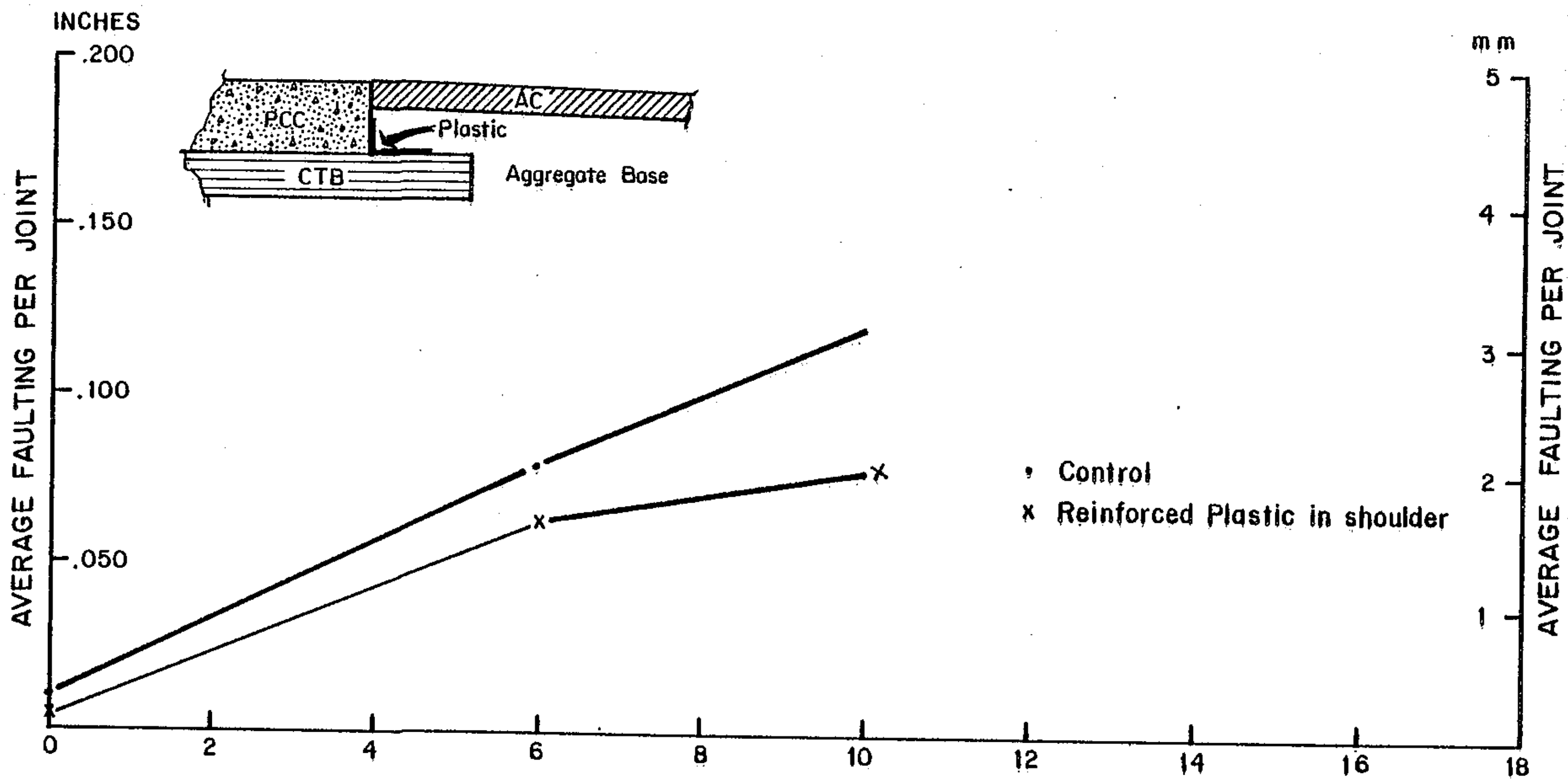


FAULTING TREND LINE

Figure B-19

10 SJ 205
N. TRACY

PAVED 1970
CT BASE



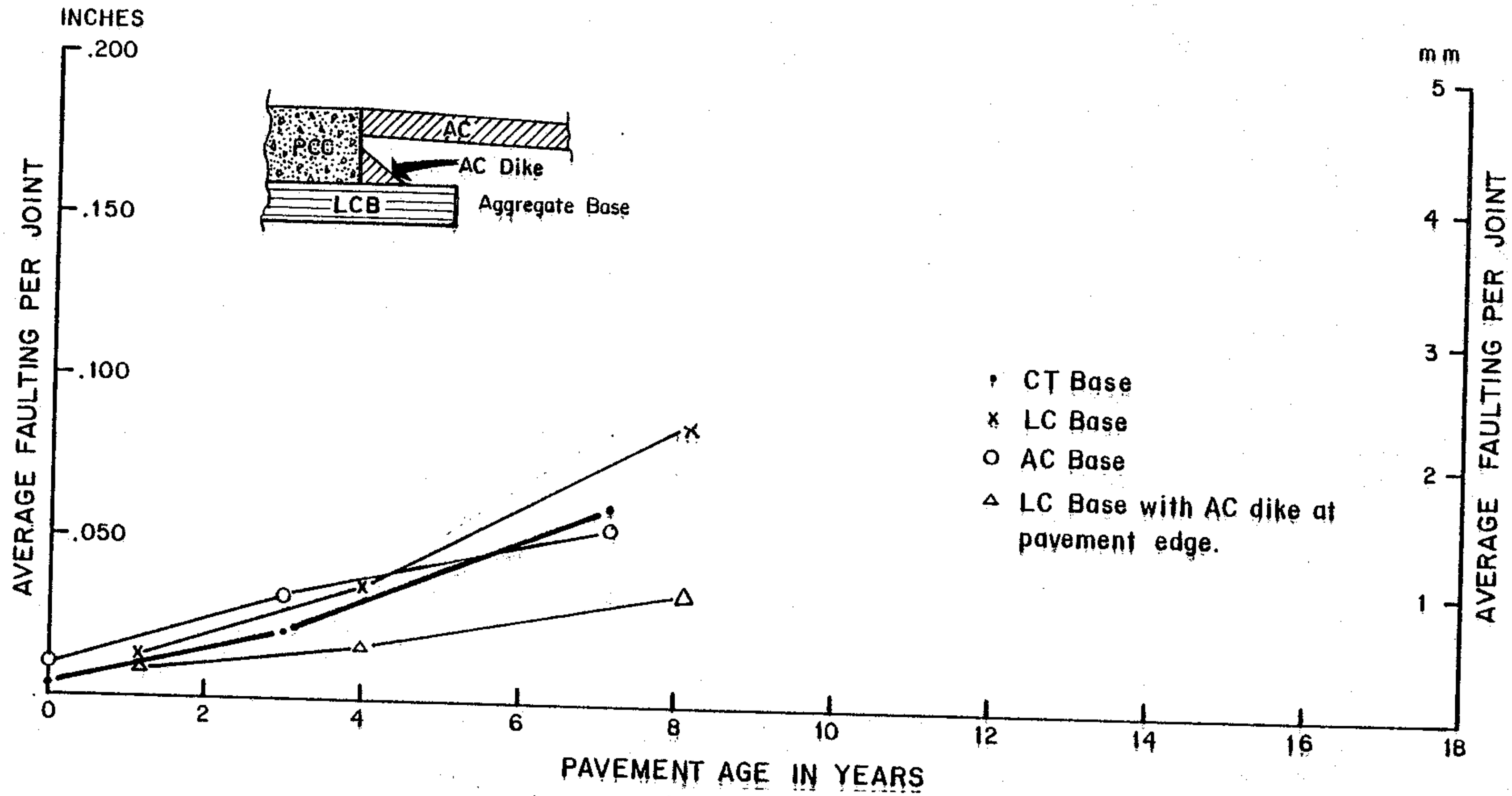
FAULTING TREND LINE

Figure B-20

05 Mon 1

FORT ORD

PAVED 1972 & 1973

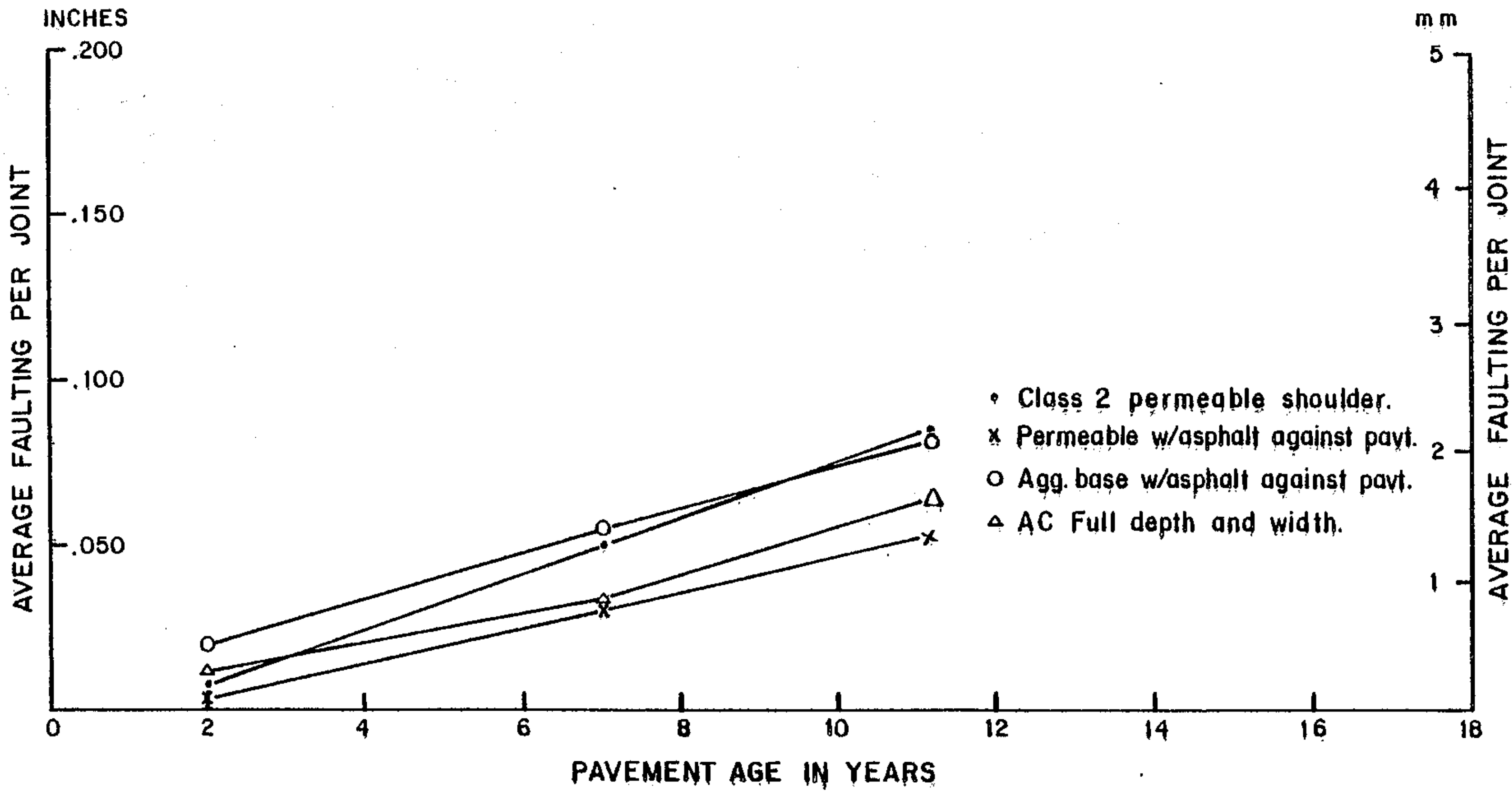


FAULTING TREND LINE

Figure B-21

03 Sac 880
SACRAMENTO

PAVED 1969
CT BASE



FAULTING TREND LINE

Figure B-22

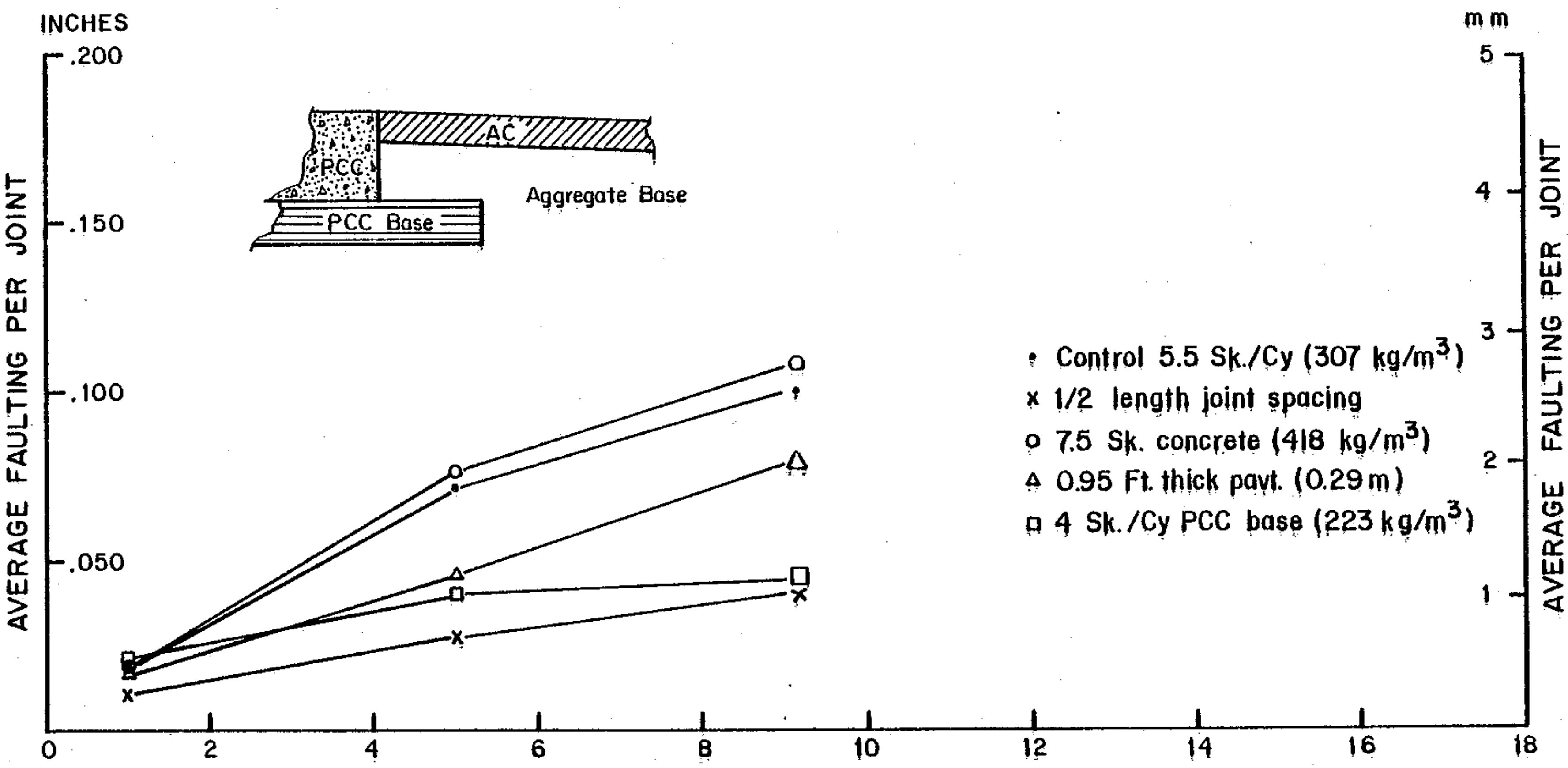
PAVEMENT JOINT FAULTING

10 SJ 5

E. TRACY (SB)

PAVED 1971

CT BASE



FAULTING TREND LINE

Figure B-23

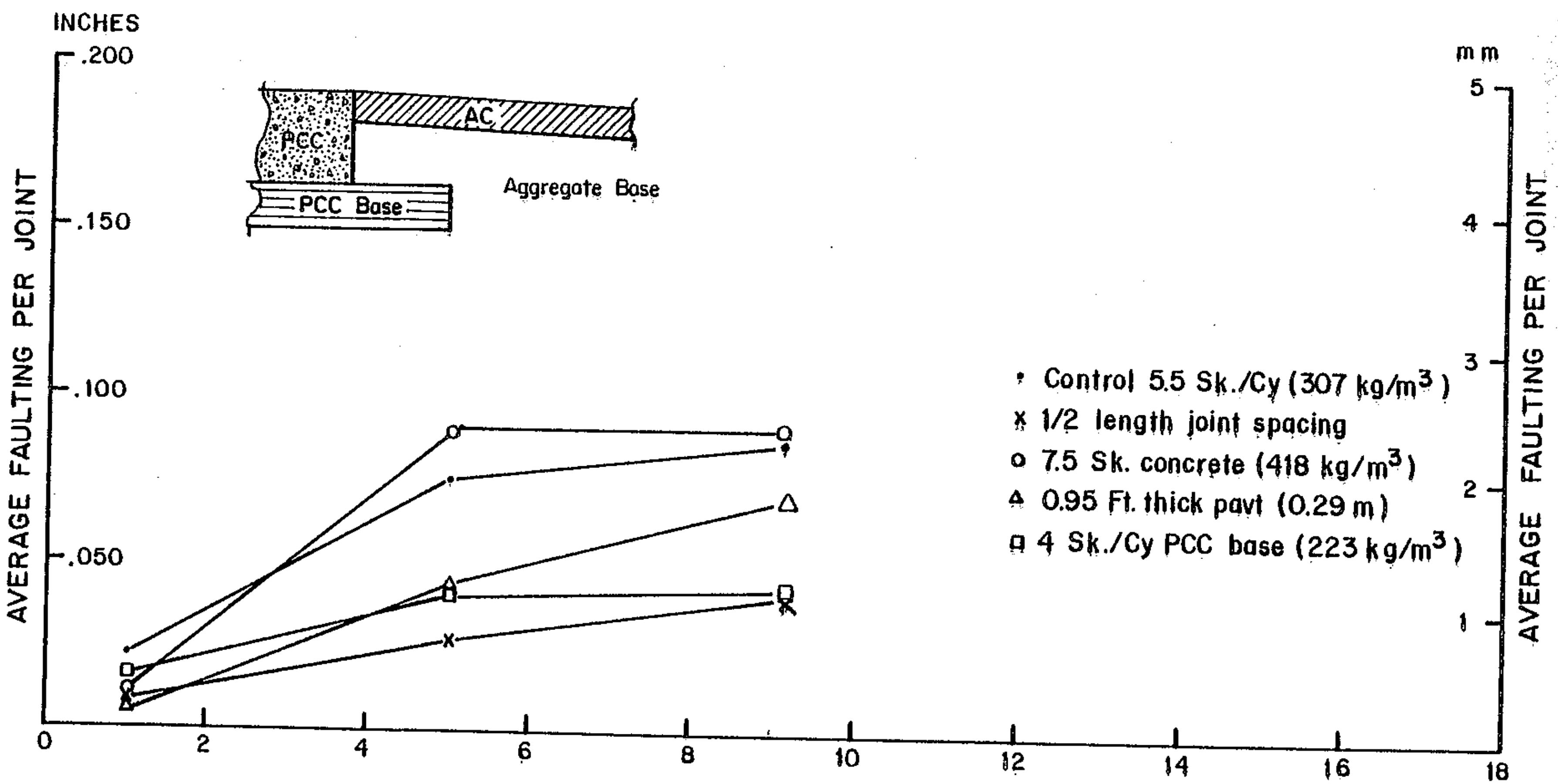
PAVEMENT JOINT FAULTING

10 SJ 5

E. TRACY (NB)

PAVED 1971

CT BASE

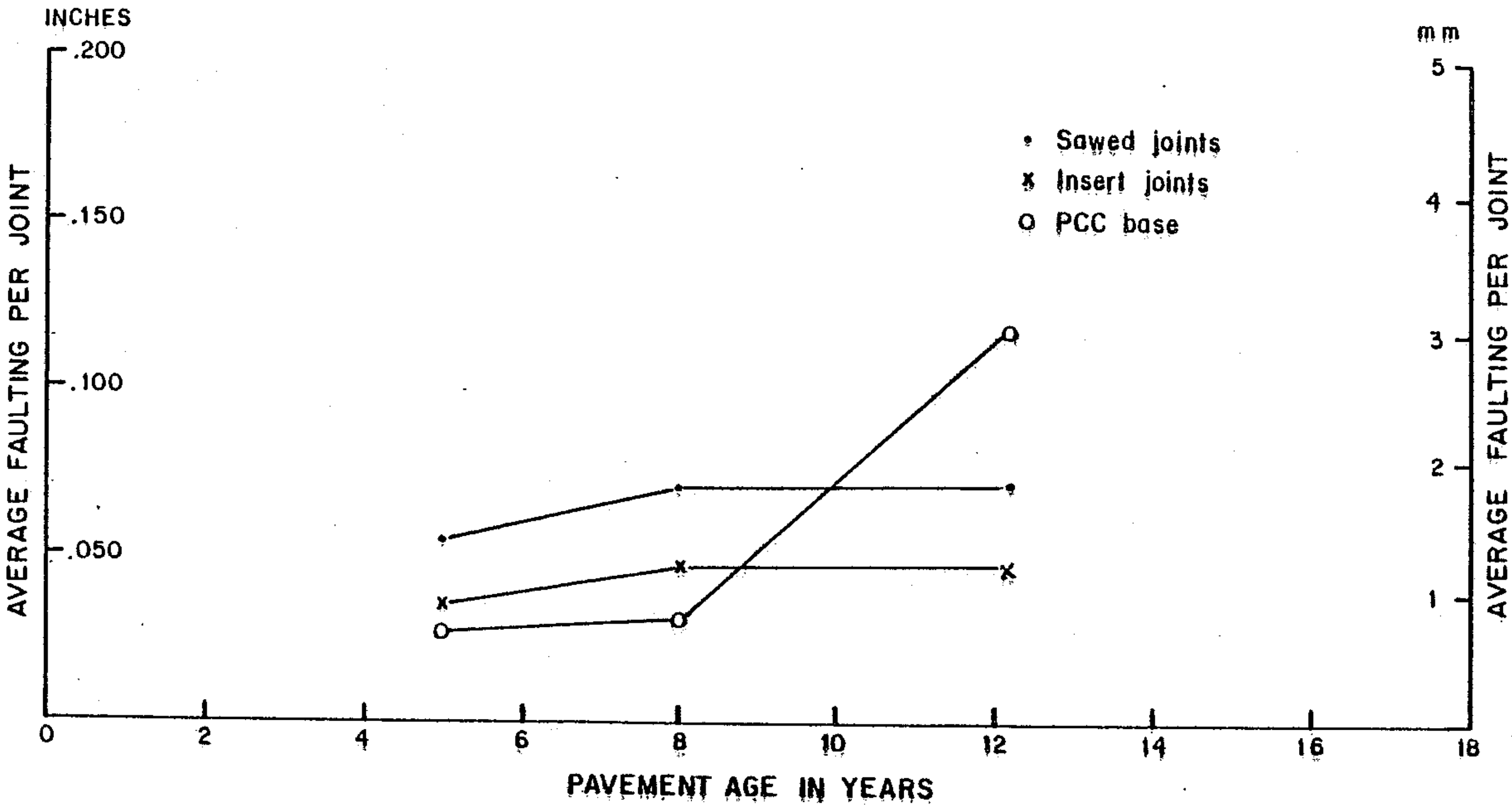


FAULTING TREND LINE

Figure B-24

II SD 8
ALPINE

PAVED 1968
CT BASE & PCC

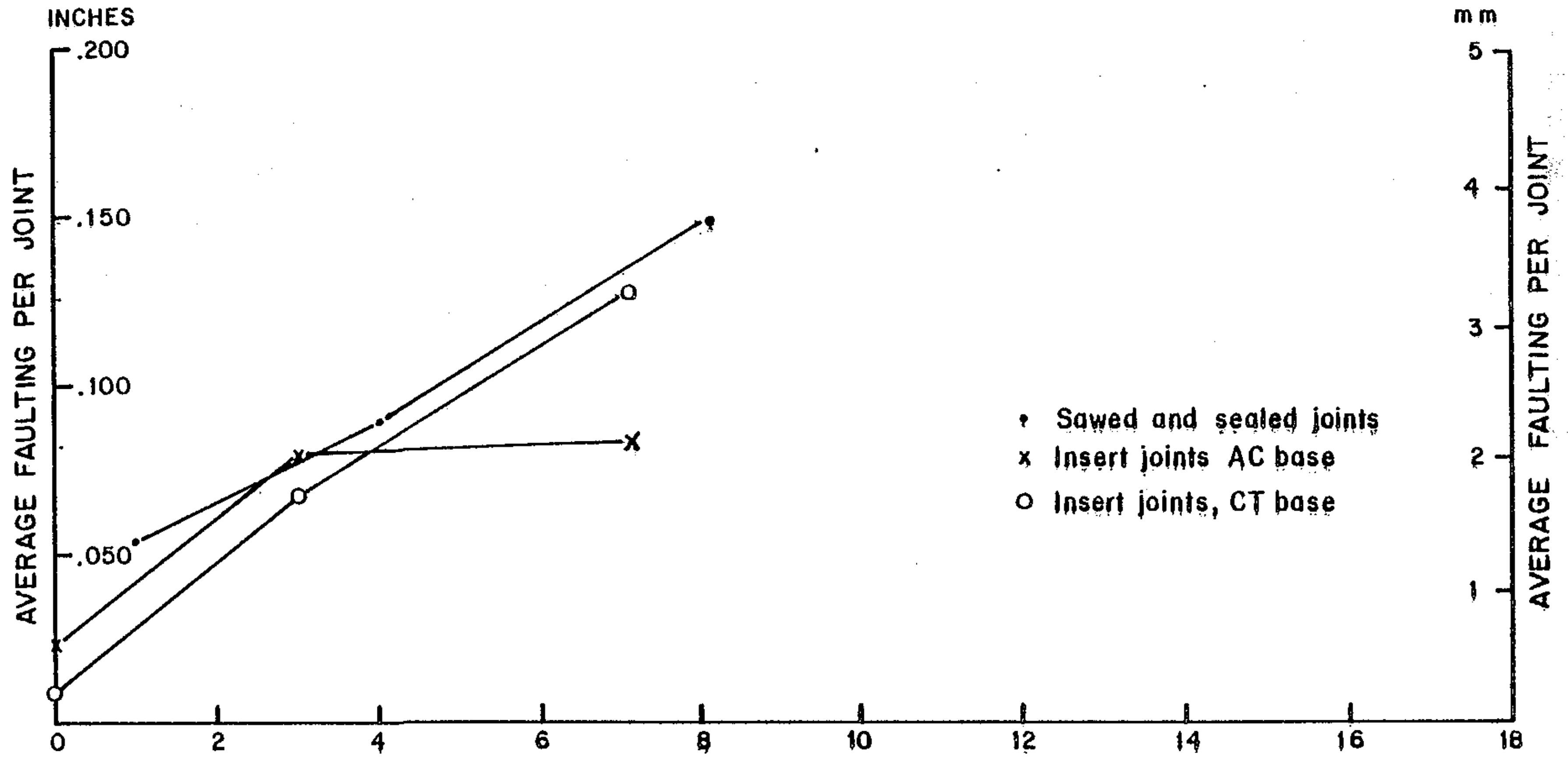


FAULTING TREND LINE

Figure B-25

02 Sis S
WEED

PAVED 1972 & 1973
CT & AC BASE



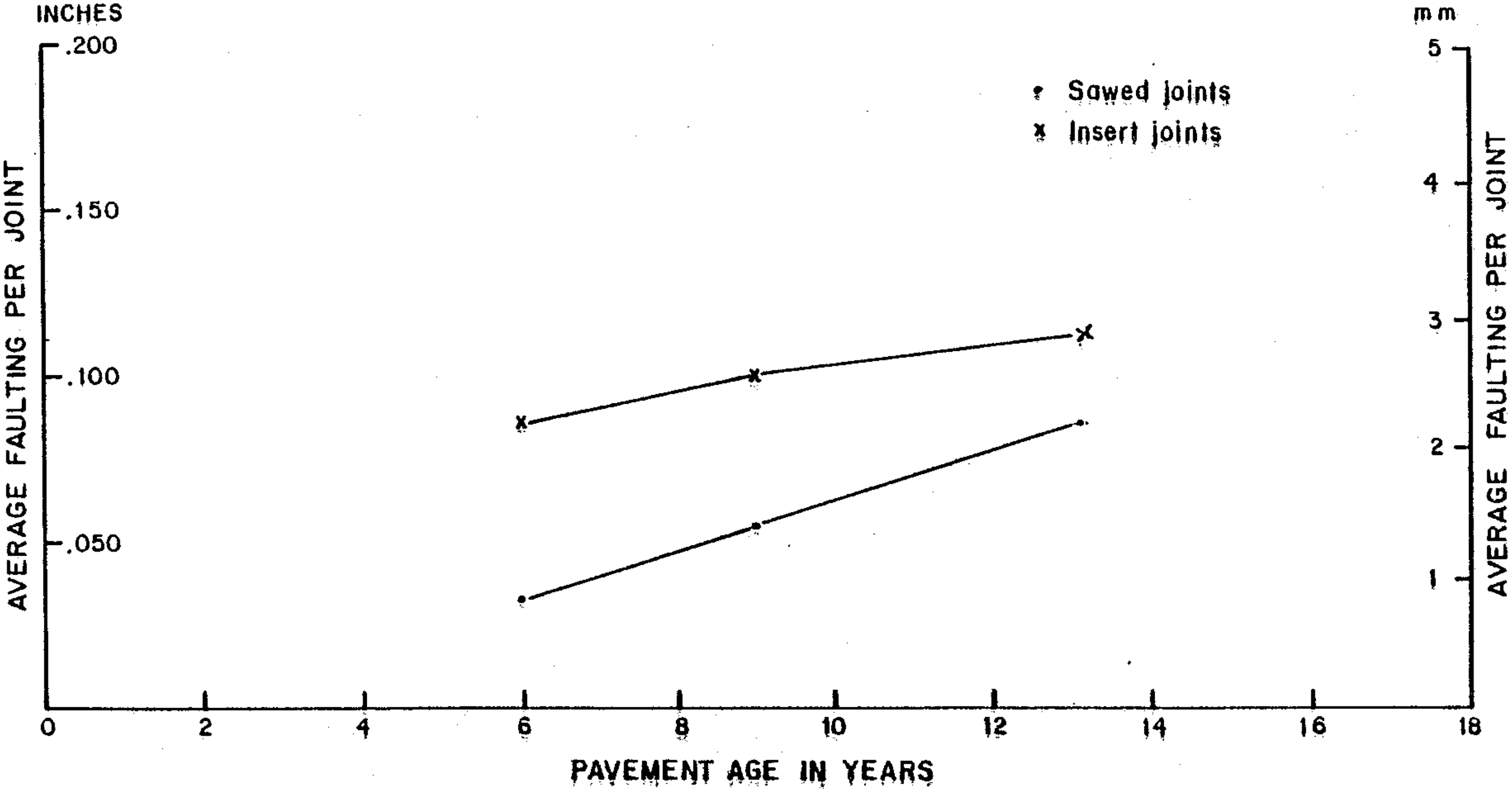
PAVEMENT AGE IN YEARS

FAULTING TREND LINE

Figure B-26

06 Mad 152
RED TOP

PAVED 1967
CT BASE

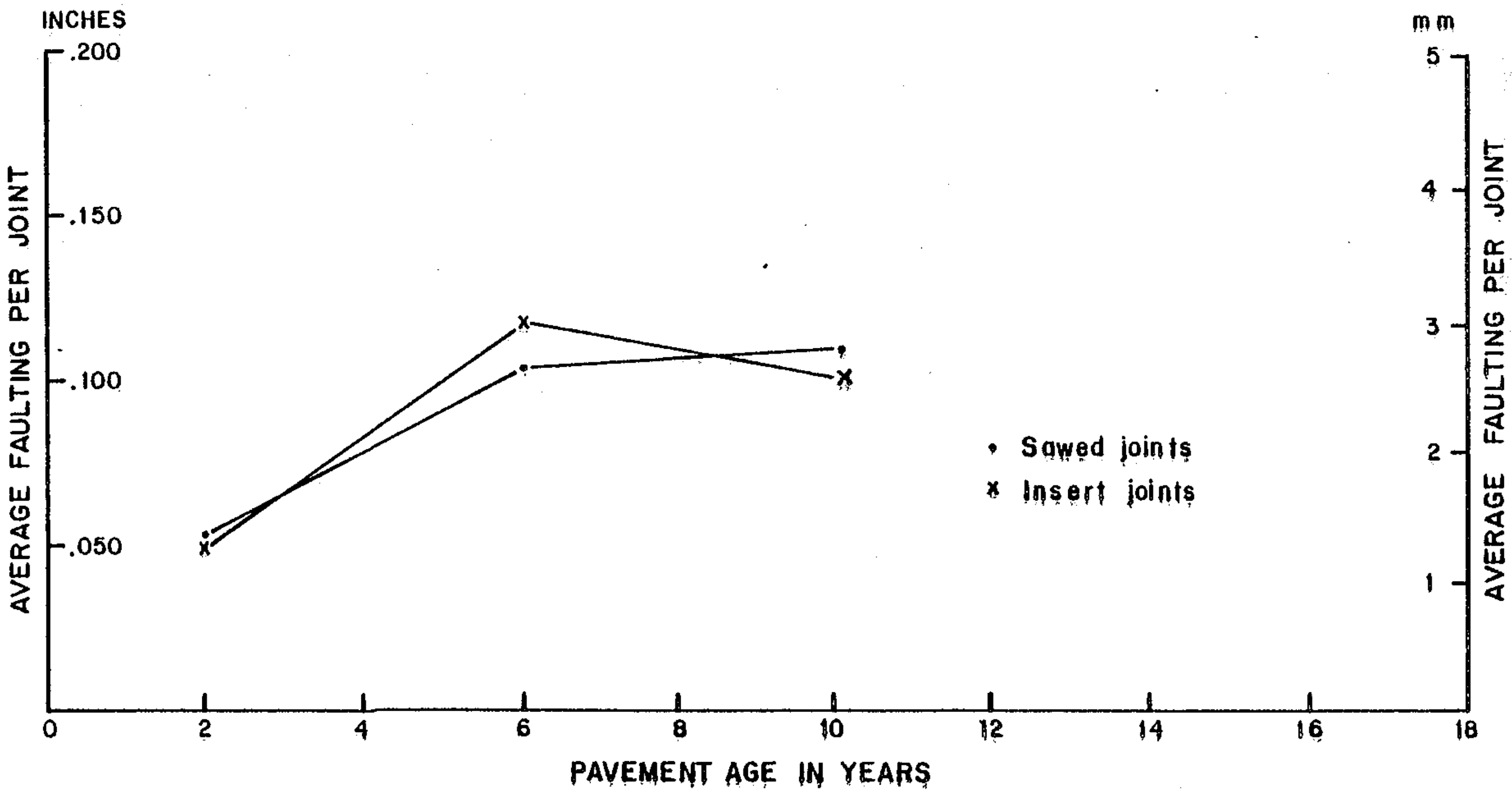


FAULTING TREND LINE

Figure B-27

02 Sis 5
YREKA

PAVED 1970
CT BASE

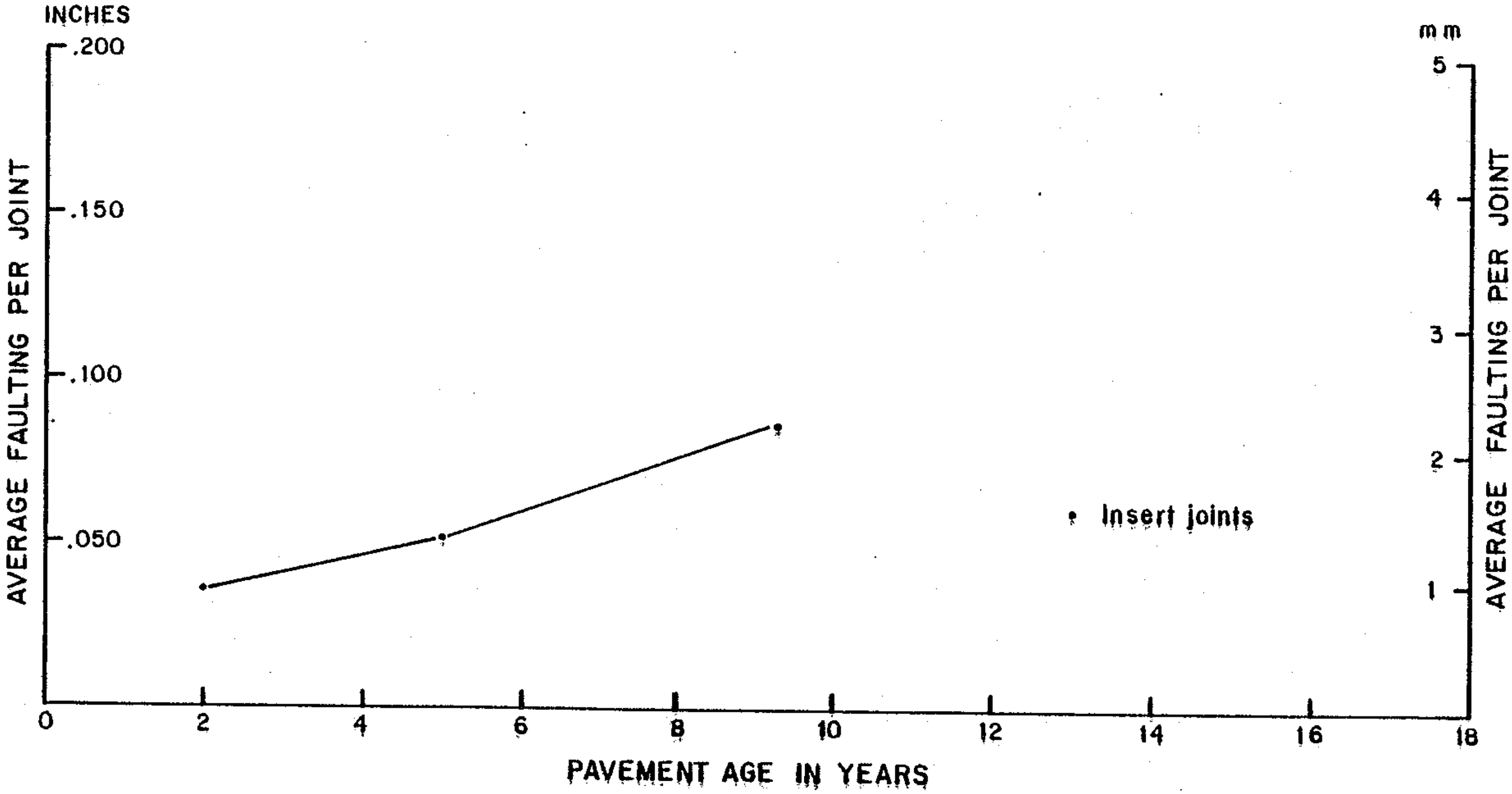


FAULTING TREND LINE

Figure B-28

06 Tul 99
GOSHEN

PAVED 1971
CT BASE

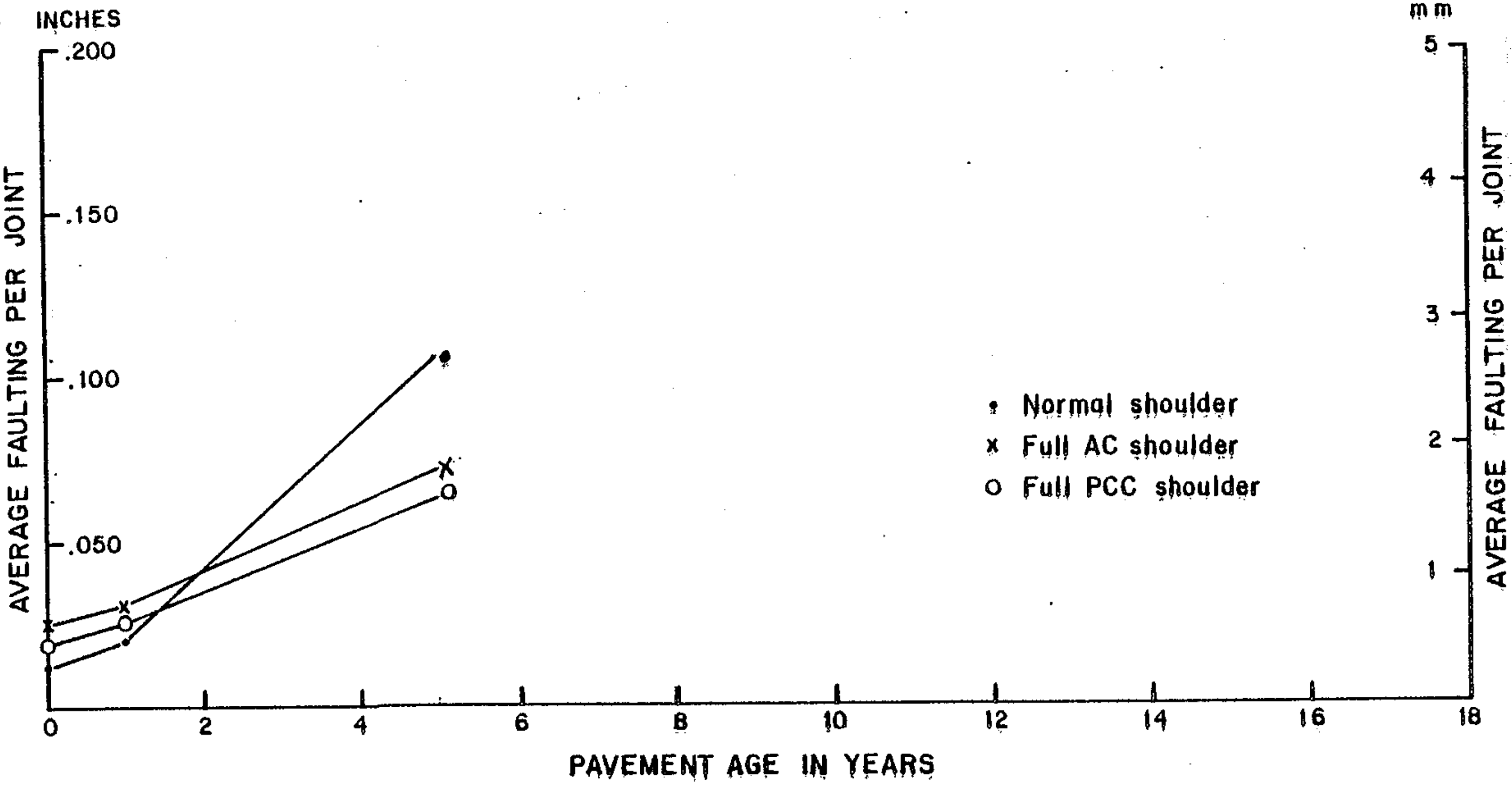


FAULTING TREND LINE

Figure B-29

04 Son 101
GEYSERVILLE

PAVED 1975
CT BASE



FAULTING TREND LINE

Figure B-30